CIGTF-SR-08-01
March 2009

UNCLASSIFIED

SEISMIC CHARACTERIZATION STUDY OF THE ADVANCED INERTIAL TEST LABORATORY (AITL) REPORT

PREPARED BY
746TH TEST SQUADRON
46TH TEST GROUP
HOLLOMAN AFB NM 88330-7850

8 DECEMBER 2008
STUDY REPORT

DISTRIBUTION STATEMENT A: Approved for Public Release: distribution is unlimited. 96ABW-2009-0125.

DESTRUCTION NOTICE: Destroy by any means that will prevent disclosure of contents or reconstruction of the document.

AIR ARMAMENT CENTER
AIR FORCE MATERIEL COMMAND
EGLIN AFB FL 32542-5000

Report Documentation Page			*Form Approved OMB No. 0704-0188*
Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.			
1. REPORT DATE **08 DEC 2008**	2. REPORT TYPE **Test Report**		3. DATES COVERED **24-07-2007 to 26-03-2008**
4. TITLE AND SUBTITLE **Seismic Characterization Study of the Advanced Inertial Test Laboratory (AITL) Report**			5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S) **Cleon Baker; William Rock**			5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **746th Test Squadron,1644 Vandergrift Road, Bldg 1265,Holloman AFB,NM,88330**			8. PERFORMING ORGANIZATION REPORT NUMBER **CIGTF-SR-08-01**
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)			10. SPONSOR/MONITOR’S ACRONYM(S) 11. SPONSOR/MONITOR’S REPORT NUMBER(S)
12. DISTRIBUTION/AVAILABILITY STATEMENT **Approved for public release; distribution unlimited**			
13. SUPPLEMENTARY NOTES			
14. ABSTRACT **The Advaned Inertial Test Laboratory (AITL) is the most seismically quiet test facility in the nation. However, due to poor isolation of newly installed environmental support equipment (ESE) and improper upkeeping of existing isolation, the seismic test environment has been compromised. In order to quantify the current seismic environment, this study was conducted from 24 July 07 to 26 March 08. This report presents the results of the study, along with strategies to improve the test envirnment. The implementation of the proposed improvements will help to ensure that AITL remains a premier test facility.**			
15. SUBJECT TERMS			

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Public Release**	**96**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

This study report has been reviewed and approved for publication.

William G. Rock	8 Dec 08
WILLIAM G. ROCK, 2d Lt, USAF **Test Manager** **746th Test Squadron**	**Date**
David W. Minto	8 DEC 08
DAVID W. MINTO, YF-03, DAF **Technical Director** **746th Test Squadron**	**Date**
Amy J. McCain	12 DEC 08
AMY J. McCAIN, Lt Col, USAF **Commander** **746th Test Squadron**	**Date**

UNCLASSIFIED

REPORT DOCUMENTATION PAGE	*Form Approved OMB No. 0704-0188*

Field	Entry
1. REPORT DATE *(DD-MM-YYYY)*	08 12 2008
2. REPORT TYPE	Study Report
3. DATES COVERED *(From - To)*	24 Jul 07 to 26 Mar 08
4. TITLE AND SUBTITLE	Seismic Characterization Study of the Advanced Inertial Test Laboratory (AITL) Report
5a. CONTRACT NUMBER	N/A
5b. GRANT NUMBER	N/A
5c. PROGRAM ELEMENT NUMBER	N/A
5d. PROJECT NUMBER	99930000
5e. TASK NUMBER	999N5001
5f. WORK UNIT NUMBER	N/A
6. AUTHOR(S)	Mr. Cleon Barker Lt William Rock
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)	746th Test Squadron 1644 Vandergrift Road Holloman AFB NM 88330-7850
8. PERFORMING ORGANIZATION REPORT NUMBER	CIGTF-SR-08-01
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	N/A
10. SPONSOR/MONITOR'S ACRONYM(S)	N/A
11. SPONSOR/MONITOR'S REPORT NUMBER(S)	N/A
12. DISTRIBUTION/AVAILABILITY STATEMENT	Distribution Statement A: Approved for Public Release: distribution is unlimited. 96ABW-2009-0125.
13. SUPPLEMENTARY NOTES	None.

14. ABSTRACT

This study determined the seismic test environment of the Advanced Inertial Test Laboratory (AITL). Based on these findings, suggestions for the improvement of the test environment have been put forward. Testing was conducted from 24 Jul 07 to 26 Mar 08.

It is recommended that AITL's environmental support equipment's passive isolation be improved. A discussion of the best way to implement the improvements are contained within.

15. SUBJECT TERMS

AITL, Seismic Testing, Advanced Inertial Test Laboratory, Inertial Navigation, Pointing Systems, Low Noise Testing

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON	19b. TELEPHONE NUMBER *(Include area code)*
U	U	U	SAR	94	Mr. Cleon Barker	575-679-1740

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39.18

THIS PAGE INTENTIONALLY LEFT BLANK.

EXECUTIVE SUMMARY

BACKGROUND

The Advanced Inertial Test Laboratory (AITL) is the most seismically quiet test facility in the nation. However, due to poor isolation of newly installed environmental support equipment (ESE) and improper upkeep of existing isolation, the seismic test environment has been compromised. In order to quantify the current seismic environment, this study was conducted from 24 Jul 07 to 26 Mar 08. This report presents the results of the study, along with strategies to improve the test environment. The implementation of the proposed improvements will help ensure that AITL remains a premier test facility.

STUDY DESCRIPTION

The transmissibility of vibration through the passive isolators of the ESE and the seismic environment of the Room 13 test pad were measured. These measurements determined which pieces of support equipment were the most seismically disturbing. The overall study objective was to determine AITL's seismic environment and use this information to plan future improvements to the facility. This objective was met.

RESULTS

ESE increased seismic disturbances up to 24 times the ambient level measured with all equipment off. The combined disturbances from the simultaneous operation of all the air handlers had the greatest effect on the seismic environment. Disturbances from individual pieces of equipment are ranked from greatest disturbance to least as follows: the air compressor, the Room 13 air handler, the fresh-air air handler, the Room 9 air handler, the Room 12 air handler, the chilled water pump, the administrative air handler and the chiller.

CONCLUSIONS AND RECOMMENDATIONS

Some ESE cause significant seismic disturbances, exceeding the seismically quiet requirements anticipated for future testing in AITL. **Improve the isolation of the ESE in order to reduce the seismic disturbances being coupled into the Room 13 test pad (R1). When ultra-clean air is**

required, utilize one of the compressors in building 1265 to supply the air to the test beds in AITL (R2).

TABLE OF CONTENTS

PAGE

THIS PAGE INTENTIONALLY LEFT BLANK.

LIST OF FIGURES

PAGE

THIS PAGE INTENTIONALLY LEFT BLANK.

LIST OF TABLES

PAGE

THIS PAGE INTENTIONALLY LEFT BLANK.

Seismic Characterization Study of the Advanced Inertial Test Laboratory (AITL) Report

1 INTRODUCTION

1.1 Background. The Advanced Inertial Test Laboratory (AITL), figure 1, is the most seismically quiet test facility in the nation. The seismic characteristics of AITL are due, in part, to its location in the Tularosa Basin, a naturally seismically quiet part of the nation away from urban and oceanic generated disturbances. Seismically quiet testing has been a core test capability of the 746th Test Squadron and has been recently re-identified as a core business objective of the squadron. This decision was supported by the 46th Test Group. Through the 1970s until the mid-1980s, AITL was used extensively for testing highly accurate inertial components of the Department of Defense’s (DoD) intercontinental ballistic missile programs. Since the mid-80s, the Hubble Space Telescope program was the only inertial program demanding a low-seismic test environment.

When AITL was constructed, the environmental support equipment (ESE) was mounted on vibration isolators and housed in a separate building, the Mechanical Building, in order to minimize the effects its operation had on the test environment. After the mid-80s, when the workload in the building decreased, replacement ESE was not properly isolated. In Dec 05, a preliminary study was completed to assess the existing seismic environment on the isolation pad in Room 13 of AITL (reference 1). This study revealed considerable degradation in the seismic environment. Since that time, a new refrigerated air conditioner (chiller) (appendix A, figure A-1) and a new air compressor (appendix A, figure A-2) were installed.

Due to the results of the Dec 05 study and the installation of the new ESE, the decision was made in Spring 2007 to conduct a new study to determine the effectiveness of passive isolation. This decision was again justified in the 2008 fiscal year, when the Hubble program had to re-accomplish testing due to noise contamination caused by the operation of the ESE. This made it clear that under normal operating conditions, the AITL facility did not meet current testing requirements. With the recent increase of interest within the DoD for the development of more accurate inertial and pointing systems, it has become all the more necessary to ensure AITL’s seismic environment is uncontaminated.

Figure 1. The Advanced Inertial Test Laboratory (AITL)

1.2 Program Chronology. Testing was conducted from 24 Jul 07 to 26 Mar 08. Table 1 provides an outline of the study chronology. Appendix B discusses the program chronology and test events in greater detail.

Table 1. Test Chronology

Start Date	End Date	Comments
24 Jul 07	6 Aug 07	Fixture fabrication and instrumentation checkout
7 Aug 07	9 Aug 07	Testing conducted in Mechanical Building
9 Aug 07	19 Dec 07	Instrumentation failure required purchase of a new analog-to-digital (A/D) converter and laptop computer
19 Dec 07	30 Jan 08	A/D converter and laptop computer checkout and resumption of testing in Mechanical Building
31 Jan 08	14 Feb 08	Testing in Room 13
14 Feb 08	4 Mar 08	Testing delayed due to sensor inconsistencies
4 Mar 08	26 Mar 08	Testing in Room 13
26 Mar 08	26 Mar 08	Follow-up testing in the Mechanical Building

1.3 Study Description. The study determined the transmissibility of vibration through the ESE passive isolation pads and their effects on the seismic environment in Room 13 of AITL. The data collected in Room 13 were analyzed in order to determine which of the individual pieces of ESE had the greatest impact on the seismic environment. The Room 13 test pad was chosen as the test area because, of all the test beds in AITL, it provided the most isolation and was the location of the Hubble program's tests. Recommendations for improvements to ESE isolation pads to reduce their effect on the seismic environment in Room 13 are provided.

1.4 Study Objectives. The overall study objective was to determine AITL's seismic environment and use this information to plan future improvements to the facility.

1.4.1 Study Objective 1. Determine the vibration generated by the newly installed air conditioning chiller and the attenuation provided by the passive isolators.

1.4.2 Study Objective 2. Determine the vibration generated by a newly installed air compressor and the attenuation provided by the passive isolators.

1.4.3 Study Objective 3. Determine the seismic environment on the test pad in Room 13 of AITL under the following conditions:

- All ESE operating.
- All equipment turned off and the chiller operating.
- All ESE turned off and the air compressor operating.
- All ESE turned off and the hot water pump operating.
- All ESE turned off and the chilled water pump operating.
- All ESE turned off and a selected air handler operating. All operational air handlers were tested in this manner.

1.4.4 Study Objective 4. Determine the vibration generated by all other environmental support equipment and the attenuation being provided by their respective passive isolators.

1.5 Limitations. Parts of objective 3 were not accomplished. The hot water pump, used for circulating hot water from the boiler for heating the building, was not mounted to the floor in the Mechanical Building. Rather, it was supported by the hot water pipe above the boiler. Additionally, turning it off for testing could have possibly damaged the boiler. Given these factors and the unit's small size, it was unlikely that the hot water pump was a significant source of seismic contamination to the pad in Room 13. Additionally, the air handlers for Rooms 8, 10, 11 and 14 were not tested.

The air handlers for Rooms 10 and 11 were inoperative and the Room 8 and Room 14 air handlers were normally not used and, as such, were not tested.

2 TEST AND EVALUATION

2.1 Study Objective 1. Determine the vibration generated by the newly installed air conditioning chiller and the attenuation provided by the passive isolators.

2.1.1 Study Method. One cluster of three PCB™ seismic accelerometers was placed on the air conditioning chiller, and an identical PCB™ cluster was placed on the concrete pad under the chiller. Two 10-minute tests were attempted but not completed because the chiller shut off before the test period was complete. Since all the other ESE was turned off, there was insufficient demand for chilled water to cause continuos chiller operation. A 4-minute test was eventually completed with the chiller operating, which was sufficient to provide adequate seismic data. See appendix C for test configuration.

2.1.2 Results. The results of this study objective are presented in figure 2. The top plot is the power spectral density (PSD) of the two vertical PCB™ seismic accelerometers which were mounted on the chiller and on the concrete pad below. The red trace represents the sensor placed on the chiller, and the green trace represents the sensor placed on the pad. This plot shows an obvious difference in the magnitude of the signals which indicates that some attenuation was provided by the isolation pad. Also, there was a large amount of vibration between 10 Hz and 20 Hz. The transfer function plots display the energy recorded on the pad divided by the energy recorded on the chiller. The transfer function plot shows attenuation between one to two orders of magnitude. The bottom plot shows the cumulative accelerations in *g* (1 *g* is defined as 9.80665 m/s^2) from both the chiller sensor (red) and the pad sensor (green) as frequency increases. The chiller generated a total cumulative acceleration of approximately 11 milli-*g*, and the pad displayed approximately 300 micro-*g*. See appendix D for a discussion of the analysis method.

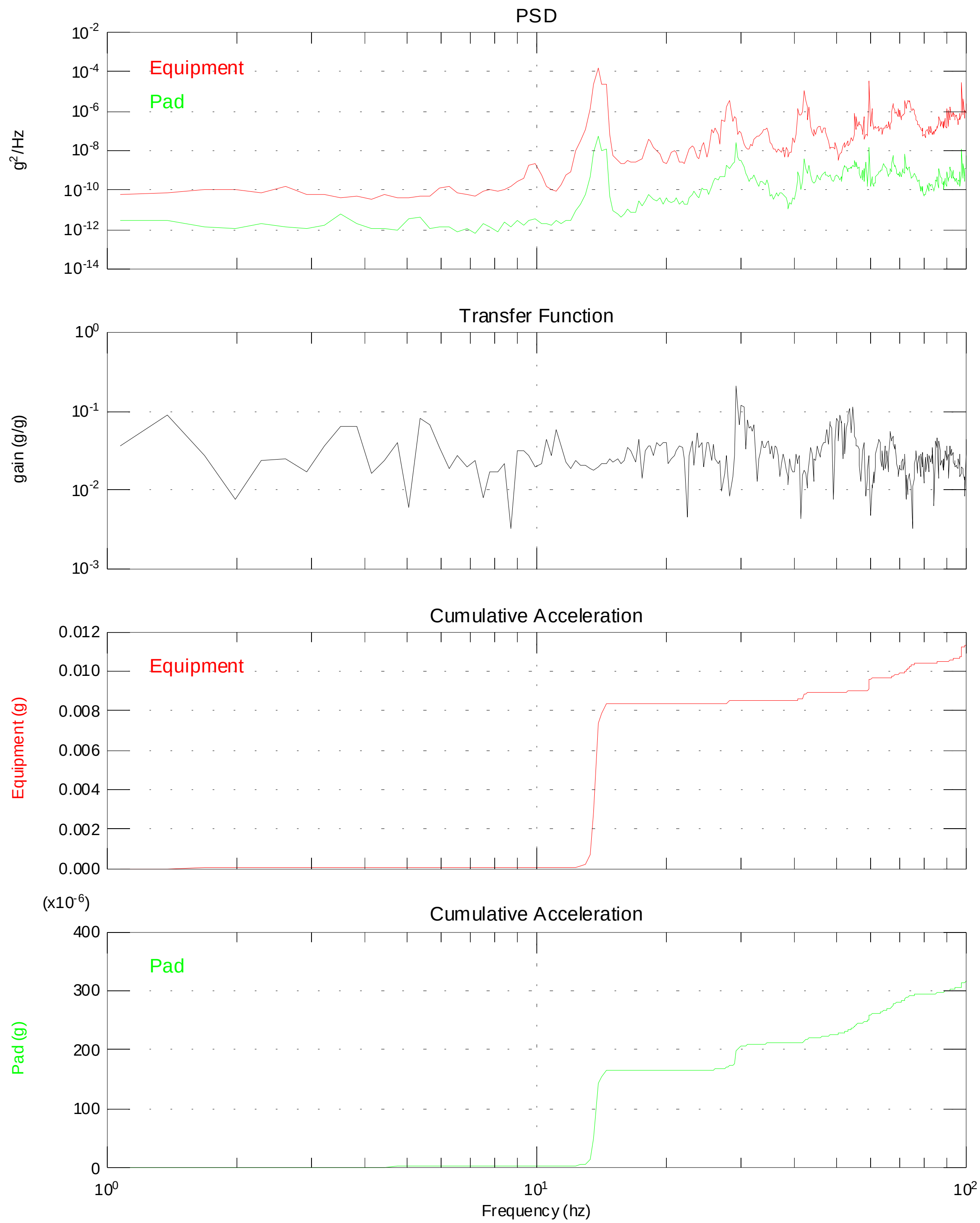

Figure 2. Seismic Disturbances Recorded at the Chiller and on the Concrete Pad as Measured by Two Vertically Oriented PCB™ Seismic Accelerometers

2.1.3 Conclusions. The results indicate that the isolation material placed between the chiller and the concrete pad was providing approximately 10.7 milli-*g* of isolation. This value will be used as baseline for future improvements.

2.2 Study Objective 2. Determine the vibration generated by a newly installed air compressor and the attenuation provided by the passive isolators.

2.2.1 Study Method. One cluster of three PCB™ seismic accelerometers was placed on the air compressor, and an identical PCB™ cluster was placed on the Mechanical Building floor in front of the compressor. The data presented in this report were collected during one 10-minute test, during which the compressor was running continuously, which was sufficient to provide adequate seismic data.

2.2.2 Results. The results of this study objective are presented in figure 3. The top plot presents the PSD of the vertical PCB™ seismic accelerometers mounted on the air compressor and on the concrete floor of the Mechanical Building in front of the air compressor. The red trace is from the sensor on the compressor, and the green trace is from the sensor on the floor. The middle plot, the transfer function, displays the energy recorded on the floor divided by the energy recorded on the air compressor. The transfer function plot shows between 0 and 4 orders of magnitude attenuation between the air compressor and concrete floor. The bottom two plots are the cumulative acceleration, in *g* as frequency increased, from both the compressor sensor (red) and pad sensor (green). These plots indicate that the compressor produced a little over 30 milli-*g* of cumulative acceleration, and the floor displayed approximately 4.5 milli-*g* of cumulated acceleration.

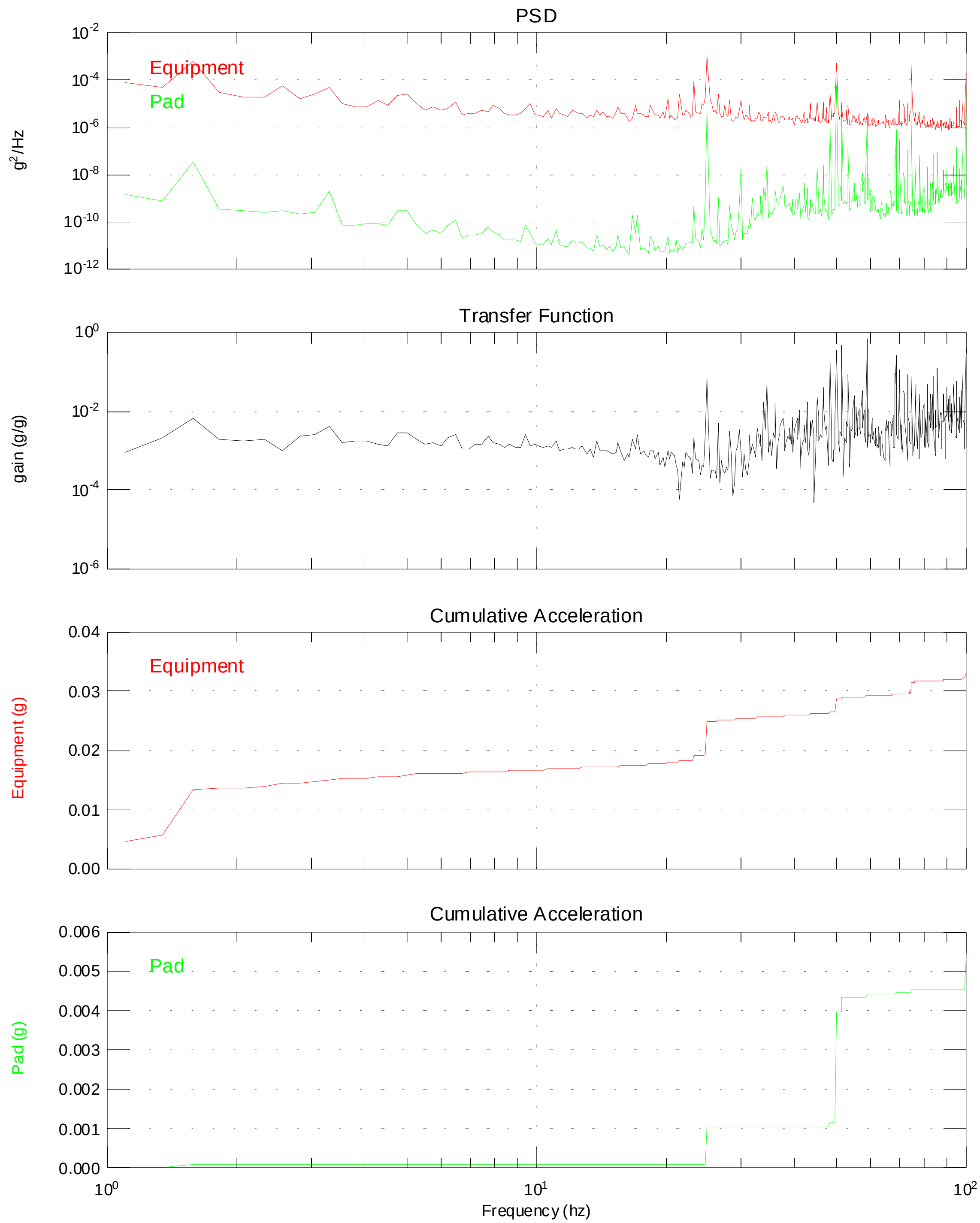

Figure 3. Seismic Disturbances Recorded at the Air Compressor and on the Concrete Pad as Measured by Two Vertically Oriented PCB™ Seismic Accelerometers

2.2.3 Conclusions. Based on the measurements taken, there is approximately 25.5 milli-*g* of isolation currently being provided. During the study it was observed that the bolts which secure the compressor to the floor are placed through the isolation material. This allows the vibrations being generated to pass from the ESE into the floor, bypassing the isolation material. This leads to the conclusion that the 25.5 milli-*g* of isolation is actually being provided by the mass of the floor, not the isolation material. The 25.5 milli-*g* of isolation will serve as a baseline for future improvements.

2.3 Study Objective 3. Measure the seismic environment on the test pad in Room 13 of AITL under the following conditions:

- All ESE operating.
- All ESE turned off and the chiller operating.
- All ESE turned off and the air compressor operating.
- All ESE turned off and the hot water pump operating.
- All ESE turned off and the chilled water pump operating.
- All ESE turned off and a selected air handler operating. All operational air handlers were tested in this manner.

2.3.1 All ESE Operating.

2.3.1.1 Study Method. For collecting seismic data on the pad in Room 13 of AITL, two clusters of seismometers were placed side by side. Each cluster was composed of a three-axis KS-2000 seismometer and three single-axis S-510 seismometers (see appendix C for test configuration). Three 15-minute tests were conducted with all of the ESE on. Although it was not an objective of this study, 15 minutes of seismic data were recorded from the two sensor clusters on the pad in Room 13 with all of the ESE listed table 2 turned off. Nine tests were conducted in this manner. As a result, two baseline conditions were generated: one with all of the ESE off and the other with all of the ESE on. Sufficient data were collected to determine the effect of all ESE operating and all ESE not operation on the Room 13 test pad.

Table 2. Environmental Support Equipment Evaluated in Objective 3

Environmental Support Equipment
Chiller
Air Compressor
Hot Water Pump
Chilled Water Pump
Fresh-air Air Handler
Administrative Air Handler
Room 9 Air Handler
Room 12 Air Handler
Room 13 Air Handler

2.3.1.2 Results. The top plot in figure 4 is the coherent power recorded from the vertical sensor in one of the KS-2000 seismometers. The energy recorded between 0.1 Hz and 0.5 Hz was the microseisms attributable to ocean waves. This energy was always present in seismic recordings and gave confidence that the sensors were working normally. The middle plot is the coherence between the two identical vertical KS-2000 seismometers. The coherence between the two sensor clusters was very poor between 0.4 Hz and 10 Hz. The bottom plot is the cumulative acceleration recorded across the frequency band from 0.01 Hz to 100 Hz. This plot shows that there was 12 micro-*g* of total cumulative acceleration recorded. There were no anomalies of significance observed in the other two axes of the seismometers.

Figure 5 is an overlay of this benign environment result (green) plotted in the same space as the disturbed environment (red) caused by the operation of the ESE (sensor 1 from figure 4). The coherence was improved from the disturbed environment in the area between 1 Hz and 10 Hz. The coherent power traces reveal that the two plots practically overlay up to approximately 4 Hz. If the coherence was better between 1 Hz and 10 Hz, there might have been more power recorded in this band. However, it can be determined that the seismic environment below 1 Hz was not being contaminated by the ESE while there was contamination in the area above 4 Hz. It should be pointed out that a 4 Hz peak was evident while the equipment was off. During the course of the study, the peak was evident in about half of the data collected. The cause of the peak could not be found in AITL or in any of the surrounding buildings. Additional attempts to determine the source have also been unsuccessful. Finally, the cumulative acceleration plot shows that the total cumulative acceleration for all of the equipment operating was 12 micro-*g* compared to the 500 nano-*g* recorded when all of the ESE were turned off. This indicates the ESE increased the seismic environment on the pad in Room 13 by a factor of almost 24.

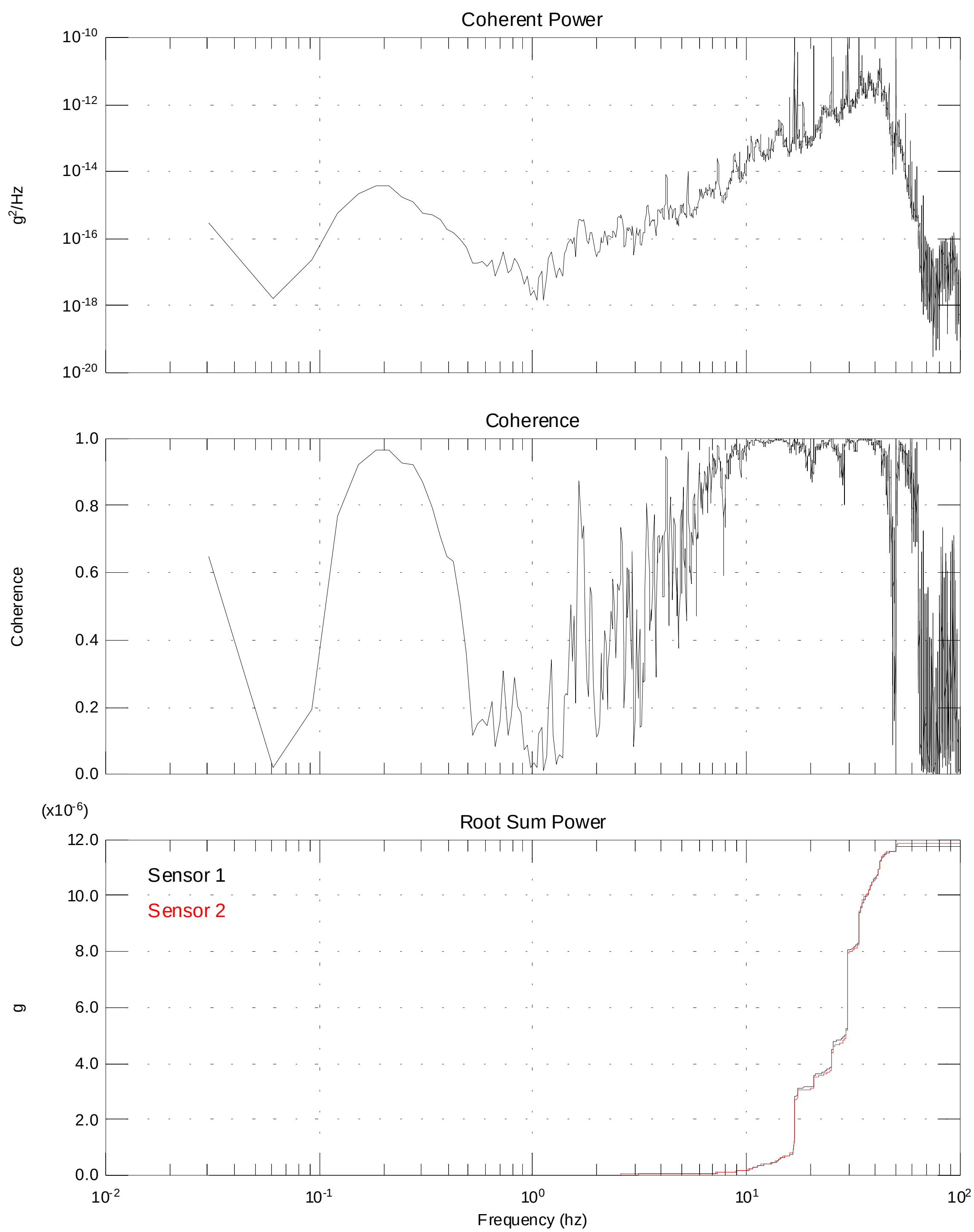

Figure 4. Seismic Disturbances Recorded on the Pad in Room 13 with All ESE Operating as Measured by Two KS-2000 Vertical Seismometers

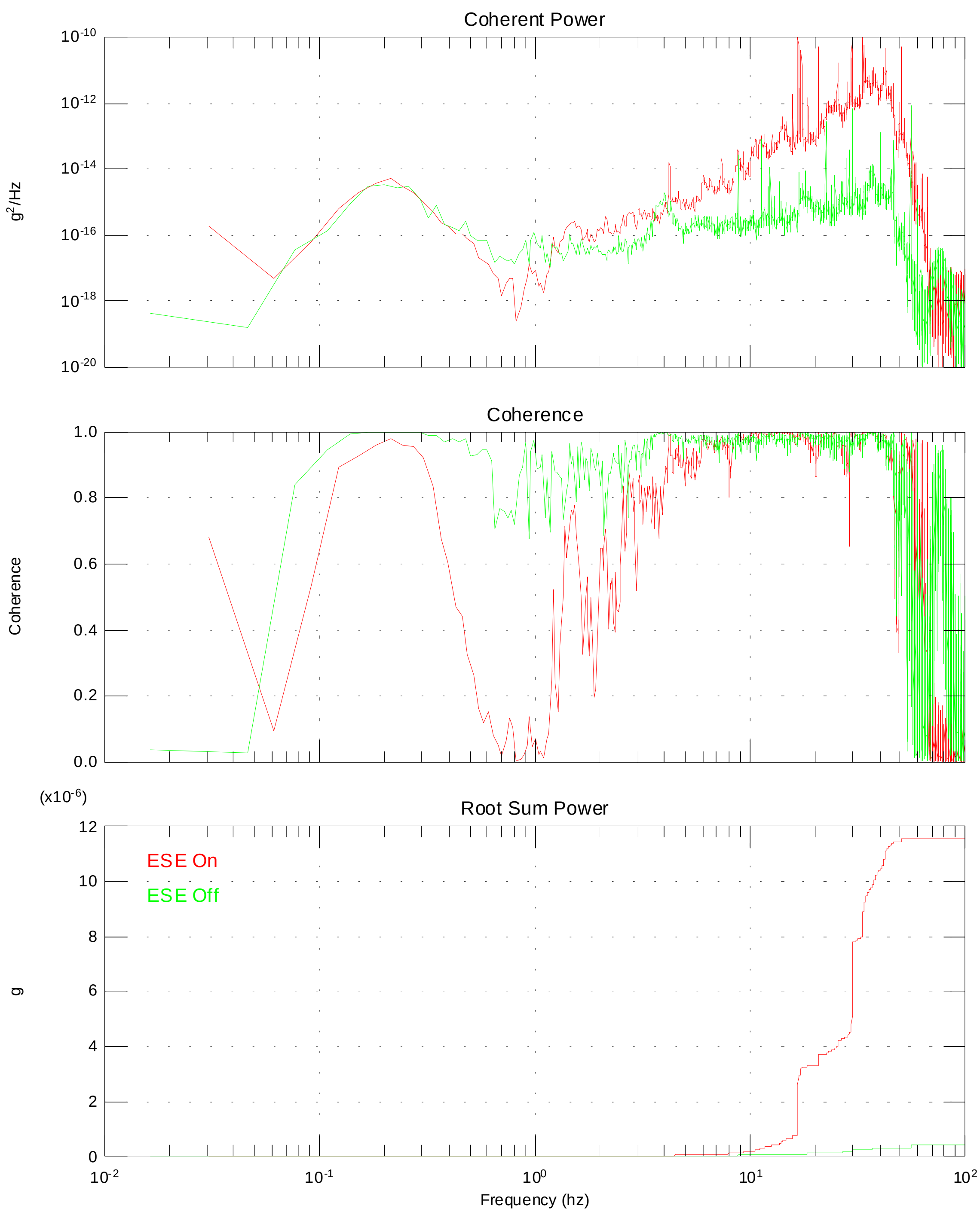

Figure 5. Seismic Disturbances Recorded on the Pad in Room 13 with All ESE off and on as Measured by Two KS-2000 Vertical Seismometers

2.3.1.3 Conclusions. The comparison of the results with all the ESE operating normally and turned off clearly shows how severely the natural seismic environment is being contaminated by the ESE. The data shows that there is 11 micro-*g* of total cumulative acceleration difference between the two environments. If the ESE were perfectly isolated, there would be no difference between the environments. While it is impossible to perfectly isolate all of the ESE, it does provide an objective for improving the seismic environment on the test pads in AITL. The difference will provide a baseline to which future improvements can be compared.

The poor coherence recorded with all of the ESE running was evident in all three axes from both the KS-2000 and the S-510 seismometers. This indicates that the two sensor plates were not moving monolithically. Future testing should be conducted with all the sensors mounted on the same plate.

2.3.1.4 Recommendation. Improve the isolation of the ESE in order to reduce the seismic disturbances being coupled into the Room 13 test pad (R1[1]).

Suggested isolation improvements for each individual piece of ESE are president in 2.3.2 through 2.3.6.

2.3.2 All ESE Turned Off and the Air Conditioning Chiller Operating.

2.3.2.1 Study Method. Data were collected using the two clusters of seismometers placed side by side on the test pad in Room 13. Each cluster was composed of a three-axis KS-2000 seismometer and three single-axis S-510 seismometers (see appendix C for test configuration). If there is no demand for the chiller from the other pieces of ESE, the chiller will turn off. Because of this requirement, four 15-minute tests were conducted with both the chiller and the chilled water pump operating, which were sufficient to provide adequate seismic data. One 15-minute test was also conducted with just the chiller operating to see if any usable data could be collected. As expected, the chiller turned off before the completion of the 15 minutes, therefore, these data were not adequate for further analysis.

[1] Numerals preceded by an R within parentheses at the end of a sentence correspond to the recommendation number tabulated in the Conclusions and Recommendations section of this report.

2.3.2.2 Results. The top plot in figure 6 shows the coherent power of one of the KS-2000 vertical sensors, the middle plot shows the coherence between two vertical sensors, and the bottom plot shows the cumulative acceleration recorded from the two sensors. The PSD of the coherent power reveals an obvious disturbance centered around 5 Hz. This disturbance was not caused by the chiller. It was a disturbance that appeared occasionally, even when all the ESE were turned off. Thus far, attempts to determine the source have been unsuccessful. Further confirmation that the chiller was not the source can be made by observing that the 5 Hz disturbance was not evident in the PSD data collected from the chiller and the pad (see figure 2). The coherence was generally good from 0.1 Hz to 0.5 Hz and from 1 Hz to 50 Hz, the area of the microseisms. The cumulative acceleration, measured from 0.01 Hz to 50 Hz, was approximately 1.7 micro-*g*.

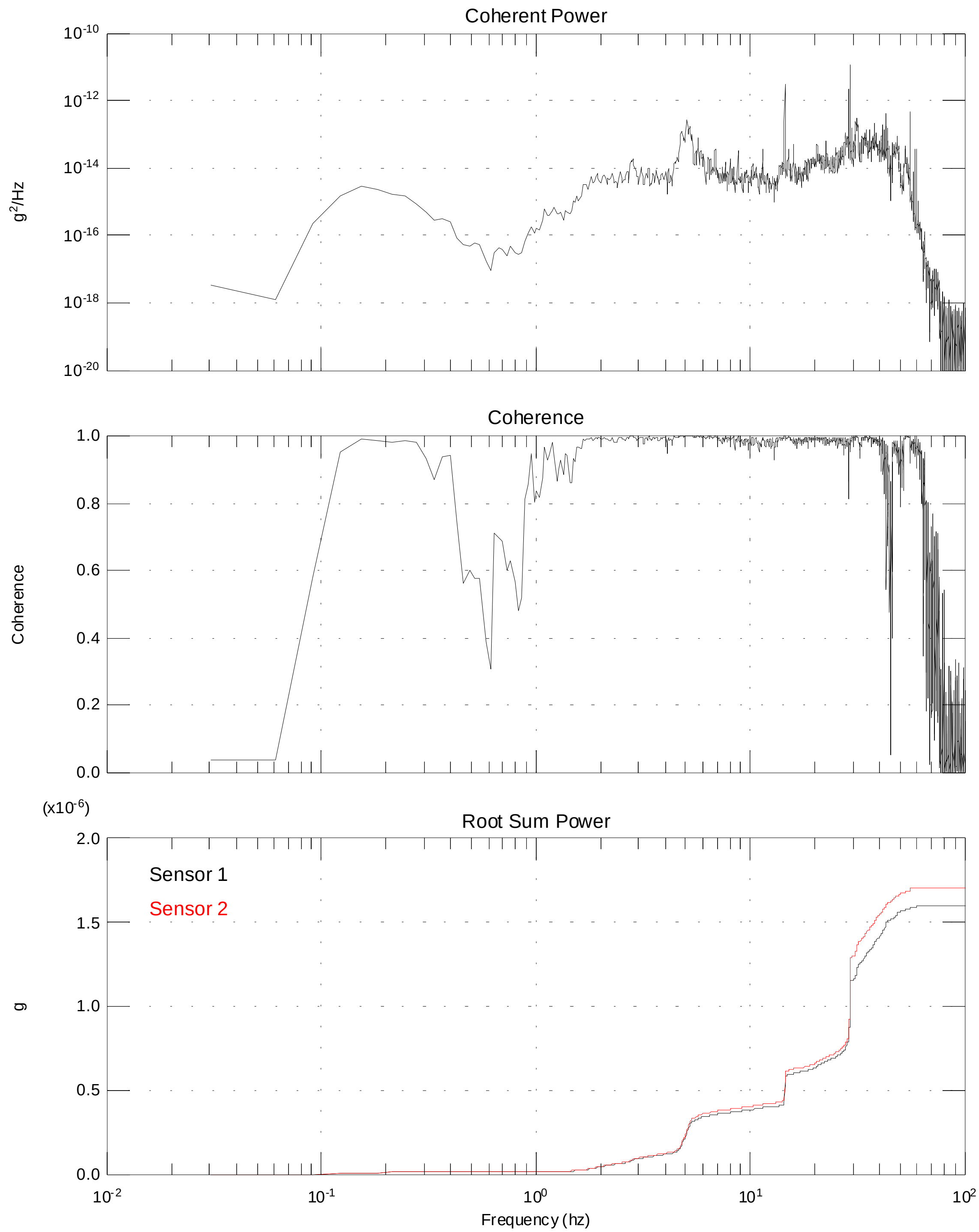

Figure 6. Seismic Disturbances Recorded on the Pad in Room 13 with the Chiller Operating as Measured by Two KS-2000 Vertical Seismometers

2.3.2.3 Conclusions. A comparison of these results to the results of the other tests performed on the Room 13 pad shows that the air conditioning chiller does not generate the most significant disturbance. However, additional improvements could further reduce the seismic disturbances produced by the chiller. The total cumulative acceleration of 1.7 micro-*g* will be used as a baseline for proposed improvements.

From an examination of the isolation pads under the chiller, figure 7, it is evident that the passive isolation material presently installed under the air conditioning chiller is not being fully utilized. Because the material has curled up, the weight is not evenly distributed across its surface. This results in the compression of only the material directly under the weight, thereby reducing the full isolation capability of the material. Additionally, vibrations from the chiller can be felt by simply placing one's hand on the cast-iron pipes where they enter and exit the building.

Figure 7. Chiller Passive Isolator

2.3.2.4 Recommendation. Improve the isolation of the ESE in order to reduce the seismic disturbances being coupled into the Room 13 test pad (R1).

Replace the current isolation material and place aluminum plates between the top of the isolation material and the chiller base. New isolation material has been identified that provides almost double the current isolation. If it is determined that further improvement is required, beyond that which will be afforded by the recommendation above, ways could be developed to replace sections of the cast iron pipe carrying the chilled water into and out of the Mechanical Building with soft flexible piping. This will isolate the vibrations close to their source and prevent the disturbance from being transferred into the walls or other parts of the facility.

2.3.3 All ESE Turned Off and the Air Compressor Operating.

2.3.3.1 Study Method. Data were collected using the two clusters of seismometers placed side by side on the test pad in Room 13. Each cluster was composed of a three-axis KS-2000 seismometer and three single-axis S-510 seismometers (see appendix C for test configuration). During testing, the air compressor was allowed to operate normally while all of the other pieces of ESE were turned off. Three 15-minute tests were conducted in this configuration, which were sufficient to provide adequate seismic data.

2.3.3.2 Results. The top plot in figure 8 shows the coherent power of one of the KS-2000 vertical sensors, the middle plot shows the coherence between two vertical sensors, and the bottom plot shows the cumulative acceleration recorded from the two sensors. The coherence was good only above 10 Hz, likely because the two separate sensor plates were not responding monolithically. The PSD of the coherent power shows a large spike at about 25 Hz. The cumulative acceleration in the bottom plot reveal most of the energy, about 10 micro-*g*, occurred at this frequency. The total cumulative acceleration for air compressor was 11 micro-*g*.

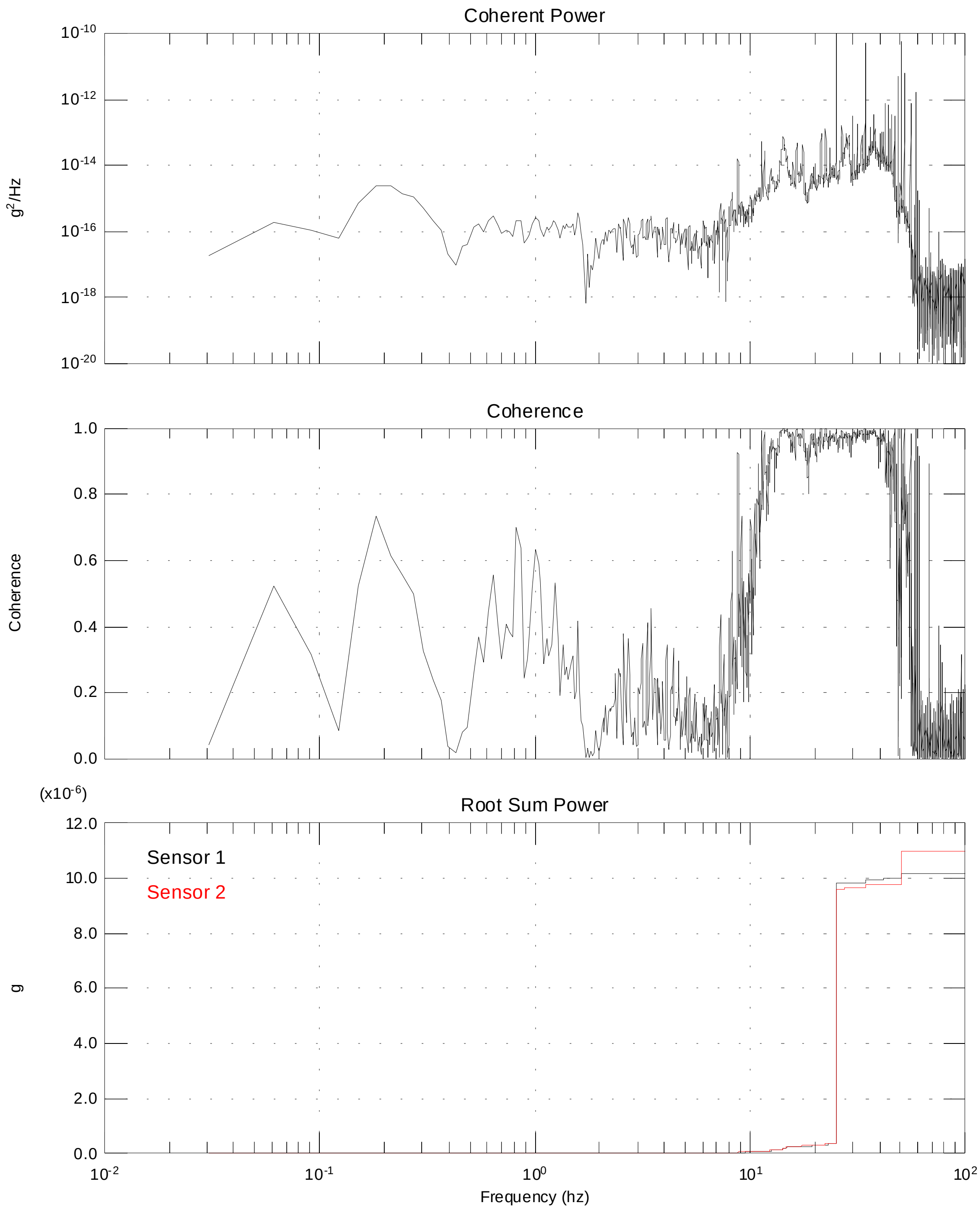

Figure 8. Seismic Disturbances Recorded on the Pad in Room 13 with the Air Compressor Operating as Measured by Two KS-2000 Vertical Seismometers

2.3.3.3 Conclusion. The total cumulative acceleration for the air compressor, 11 micro-*g*, was greater than that of any other individual piece of ESE and therefore requires improved isolation. The 11 micro-*g* value will be used as a base line for future improvements.

2.3.3.4 Recommendation. Improve the isolation of the ESE in order to reduce the seismic disturbances being coupled into the Room 13 test pad (R1).

Replace all thermostats and pneumatic actuators with digital thermostats and actuators, eliminating the need for the air compressor along with its seismic disturbances. Alternatively, make significant improvements to the compressor's isolation. The air compressor could be mounted on a 4-foot diameter 6-inch thick steel disk allowing the energy from the compressor to be transferred into the steel disk. This would also lower the center of gravity of the compressor, reducing its tendency to oscillate like an inverted pendulum. The air compressor and plate would then be placed on a second steel disk of the same size with isolation material sandwiched between the two disks. Finally, isolation material would be placed between the second steel disk and the floor (figure 9). This would allow energy transferred from the top steel disk through the isolation material to be absorbed into the lower steel disk. The isolation material between the lower disk and floor would further attenuate the vibrations. Commercially available isolation material is advertised as capable of supporting 50 lb/in^2. The weight of the steel plates will not affect the degree of isolation being provided. If additional isolation is required, the isolation material could be replaced with pneumatic isolators, most likely in the form of air bags, which are highly regarded for the amount of attenuation they provide.

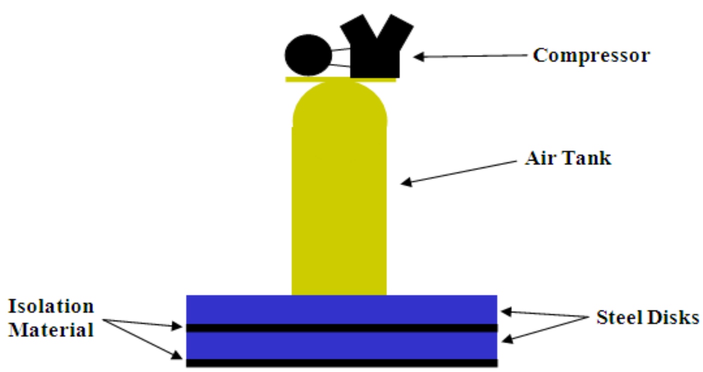

Figure 9. Proposed Isolation System

2.3.4 All ESE Turned Off and the Hot Water Pump Operating. This was not accomplished. See Limitations, paragraph 1.5, for further information.

2.3.5 All ESE Turned OFF and the Chilled Water Pump Operating.

2.3.5.1 Study Method. Data were collected using the two clusters of seismometers placed side by side on the test pad in Room 13. Each cluster was composed of a three-axis KS-2000 seismometer and three single-axis S-510 seismometers (see appendix C for test configuration). During testing, the chilled water pump was allowed to operate normally while all of the other pieces of ESE were turned off. Three 15-minute tests were conducted in this configuration, which were sufficient to provide adequate seismic data. A photograph of the chilled water pump is presented in appendix A, figure A-3.

2.3.5.2 Results. The top plot in figure 10 shows the coherent power of one of the KS-2000 vertical sensors, the middle plot shows the coherence between two vertical sensors, and the bottom plot shows the cumulative acceleration recorded from the two sensors. The coherence of the data from this test was good up to 50 Hz, with the exception of around 1 Hz. Around 1 Hz, the seismic activity was typically very low, resulting in a higher signal-to-noise ratio. This resulted in lower coherence. The PSD of the coherent power shows a large spike at 30 Hz and some minor disturbances below that frequency. The cumulative acceleration also revealed a little over 500 nano-*g* below the 30 Hz spike and then a little over 1 micro-*g* of energy in the 30 Hz spike. The total cumulative acceleration for the chilled water pump was approximately 2.6 micro-*g*.

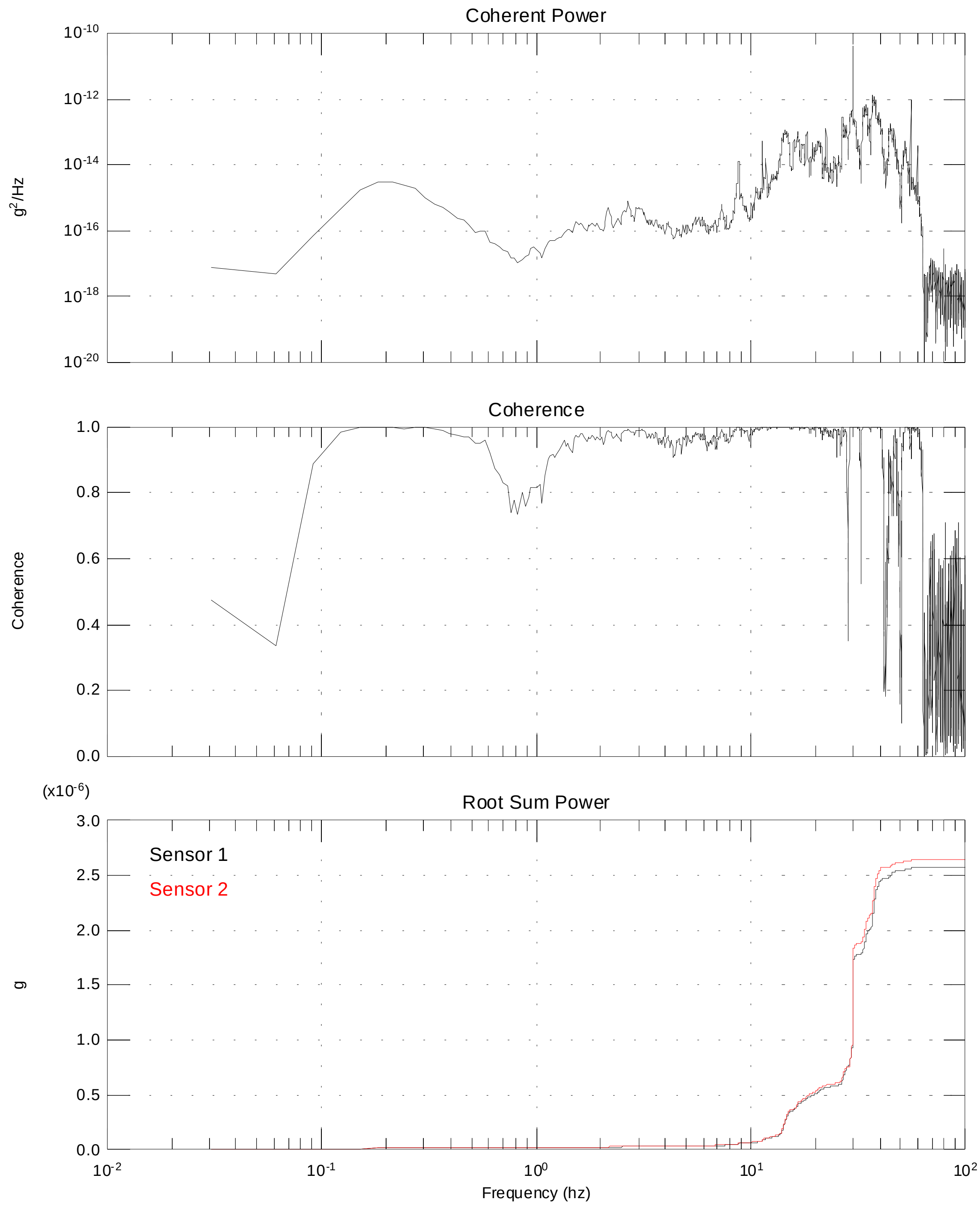

Figure 10. Seismic Disturbances Recorded on the Pad in Room 13 with the Chilled Water Pump Operating as Measured by Two KS-2000 Vertical Seismometers

2.3.5.3 Conclusion. The chilled water pump produced a total cumulative acceleration of 2.6 micro-*g* on the test pad. Compared to other pieces of ESE, the chilled water pump was found to be a small contributor to the overall seismic disturbance to the isolation pad in Room 13. However, additional improvements could further reduce the seismic disturbances produced by the chilled water pump. This value will be used as a baseline for future improvements.

2.3.5.4 Recommendation. Improve the isolation of the ESE in order to reduce the seismic disturbances being coupled into the Room 13 test pad (R1).

Request that Civil Engineering decommission this unit and activate the second chilled water pump that is presently installed in the Mechanical Building. At one time, there were two redundant air conditioning chillers and chilled water pumps supporting the AITL facility. One of the two original air conditioning chillers failed, was removed and was not replaced. The second original chilled water pump is still connected to the chilled water system in parallel with the chilled water pump which was examined during the study. By shaking each pump's isolation platform, it appeared that the second pump was on a softer suspension and may have provided more isolation. Before it can be determined if the second pump is less seismically disturbing, Civil Engineering would have to flush out the unit, removing any buildup, and connect the pump to the chilled water system. Once this is accomplished, further data should be collected in order to ensure that the second chilled water pump generates less disturbance.

2.3.6 All ESE Turned Off and a Selected Air Handler Operating.

2.3.6.1 Study Method. Not all of the air handlers were tested as stated in the objective. The air handlers for Rooms 10 and 11 were inoperative and the Room 8 and Room 14 air handlers are normally not used and, as such, were not tested. The results of the test for the remaining air handlers are presented below. When data were collected, two clusters of seismometers were placed side by side on the test pad in Room 13. Each cluster was composed of a three-axis KS-2000 seismometer and three single-axis S-510 seismometers (see appendix C for test configuration). During testing, the selected air handler was allowed to operate normally while all of the other pieces of ESE were turned off. Two 15-minute tests were conducted for the fresh-air air handler, one for the administrative air handler, two for the Room 9 air handler, three for the Room 12 air handler and two for the Room 13 air handler. While it was not a stated objective, one 15-minute test was conducted with all of the air handlers running. Sufficient data were collected to determine the effect of the air handlers on the Room 13 test pad. See appendix A, figure A-4 for a photograph of a representative air handler and figure A-5 for a photograph of the Room 13 air handler.

2.3.6.2 Results. Each individual air handler contributed seismic disturbances of varying magnitudes and frequencies. Collectively, they produced a disturbance of 12 micro-*g*, slightly more than the air compressor. The results for each of the tested air handlers are presented below.

2.3.6.2.1 Fresh-air Air Handler. The top plot in figure 11 shows the coherent power of one of the KS-2000 vertical sensors, the middle plot shows the coherence between two vertical sensors, and the bottom plot shows the cumulative acceleration recorded from the two sensors. The coherence from this test looks typical, as does the PSD of coherent power. From the cumulative acceleration plot, it is clear that about 1 micro-*g* of acceleration was recorded at a little less than 20 Hz and approximately 3 micro-*g* of acceleration at about 25 Hz. The total cumulative acceleration of the fresh-air air handler is approximately 5 micro-*g*.

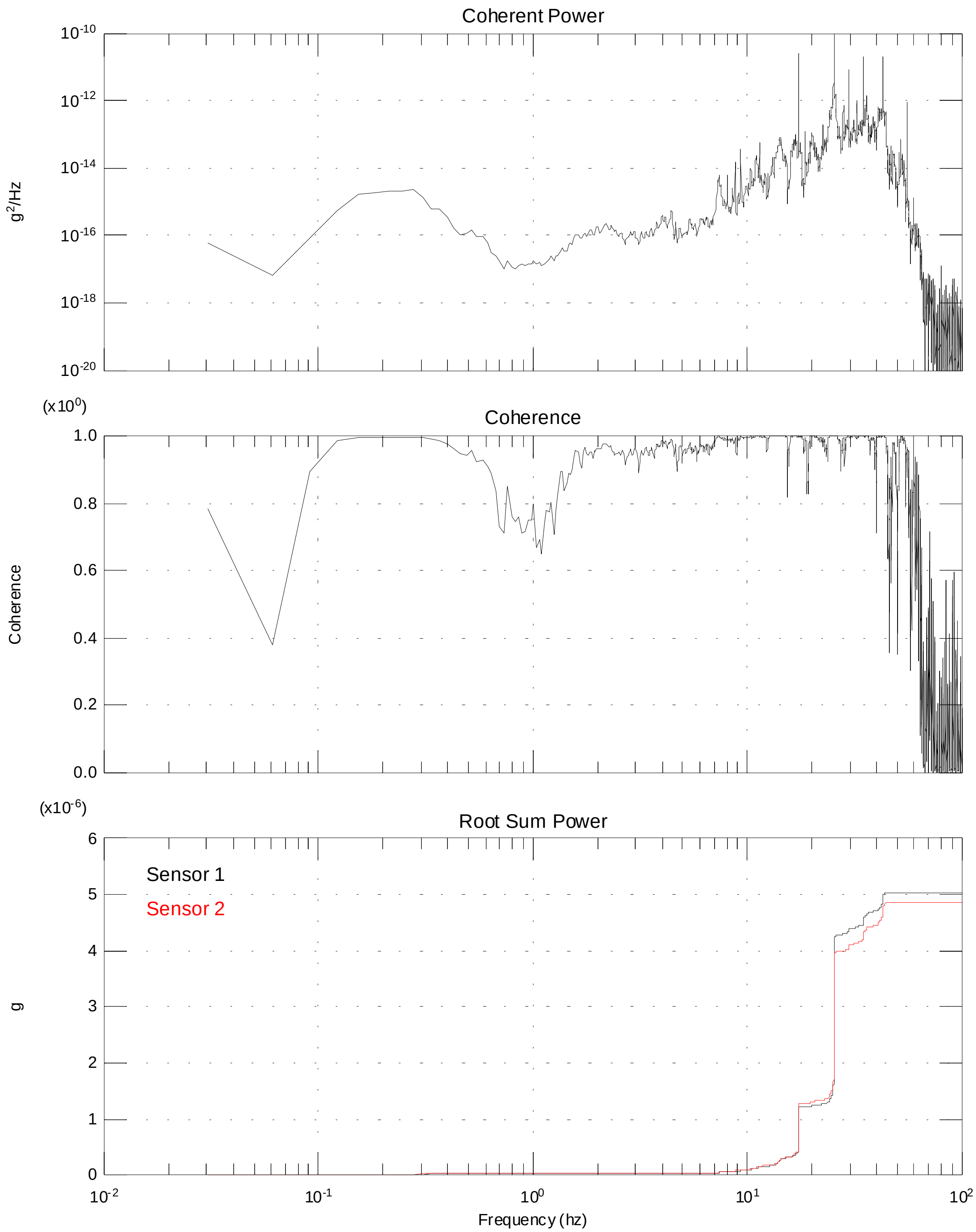

Figure 11. Seismic Disturbances Recorded on the Pad in Room 13 with the Fresh-air Air Handler Operating as Measured by Two KS-2000 Vertical Seismometers

2.3.6.2.2 Administrative Air Handler. The top plot in figure 12 shows the coherent power of one of the KS-2000 vertical sensors, the middle plot shows the coherence between two vertical, sensors and the bottom plot shows the cumulative acceleration recorded from the two sensors. The coherence between the two vertical KS-2000 sensors in the frequency range of 1 Hz to 10 Hz was lower than what was seen in the other air handler tests. The reason for this is unknown. The coherent power displayed more power in the 1 Hz to 2 Hz area than is typically seen, leading to the conclusion that there must have been independent motion of the sensor clusters. The cumulative acceleration shows approximately 300 nano-*g* around 5 Hz, 1.2 micro-*g* at 20 Hz and approximately 300 nano-*g* at 30 Hz. The total cumulative acceleration of the administrative air handler is approximately 2 micro-*g*.

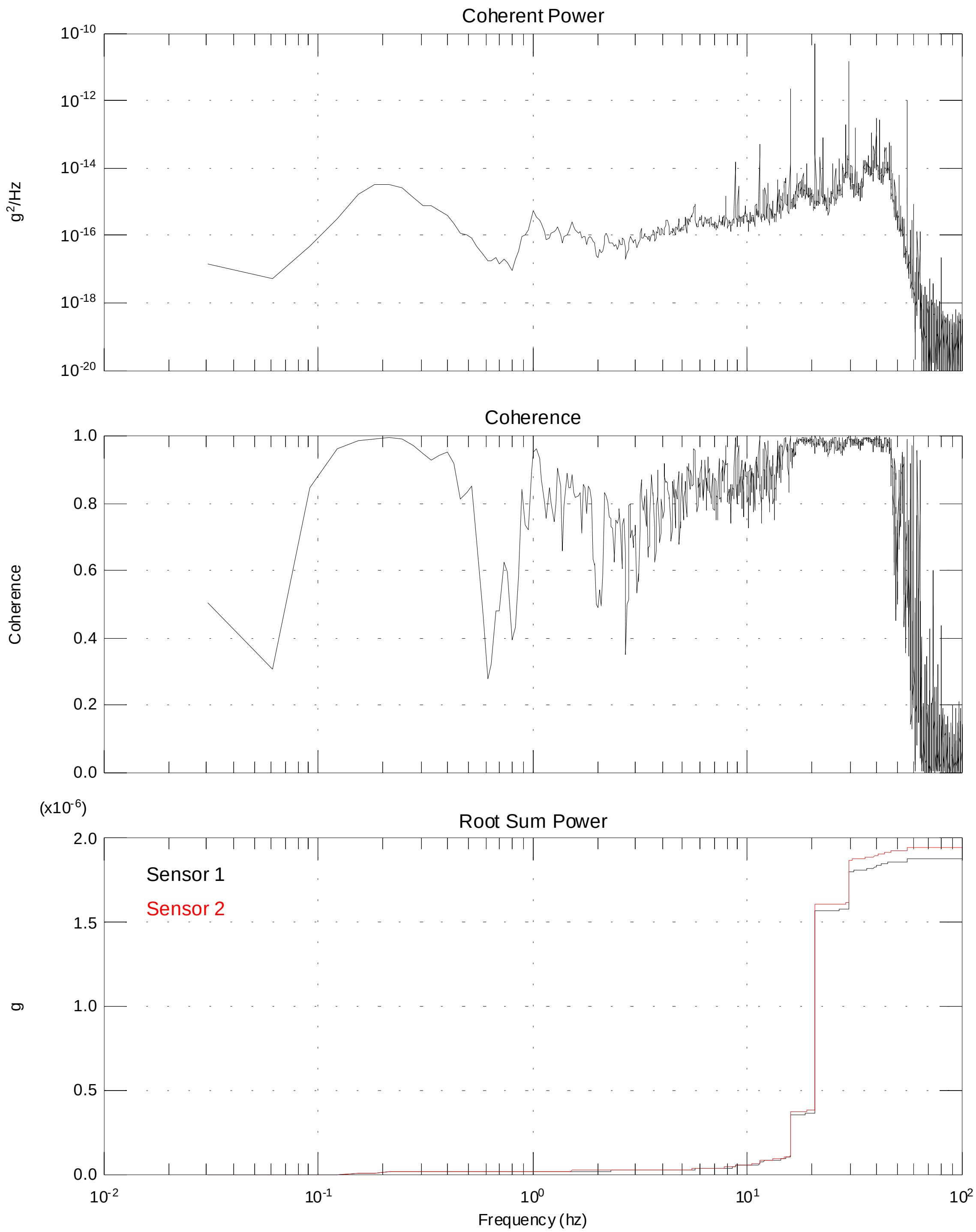

Figure 12. Seismic Disturbances Recorded on the Pad in Room 13 with the Administrative Air Handler operating as Measured by Two KS-2000 Vertical Seismometers

2.3.6.2.3 Room 9 Air Handler. The top plot in figure 13 shows the coherent power of one of the KS-2000 vertical sensors, the middle plot shows the coherence between two vertical sensors, and the bottom shows the cumulative acceleration recorded from the two sensors. This test data displayed reasonable coherence across the frequency band. The coherent PSD plot contains a peak at 9 Hz, a spike at around 15 Hz, a smaller spike at around 18 Hz and a large spike at 30 Hz. The cumulative acceleration plot revealed very little energy below 10 Hz. The data shows a few hundred nano-*g* in the area of 15 Hz and another 100 nano-*g* around 18 Hz. The significant energy occurs at 30 Hz with a magnitude of about 1 micro-*g* and then increases steadily as frequency increases up to about 45 Hz. At 45 Hz, the KS-2000 seismometer reaches its upper bandwidth. The total cumulative acceleration recorded from the Room 9 air handler is almost 5 micro-*g*.

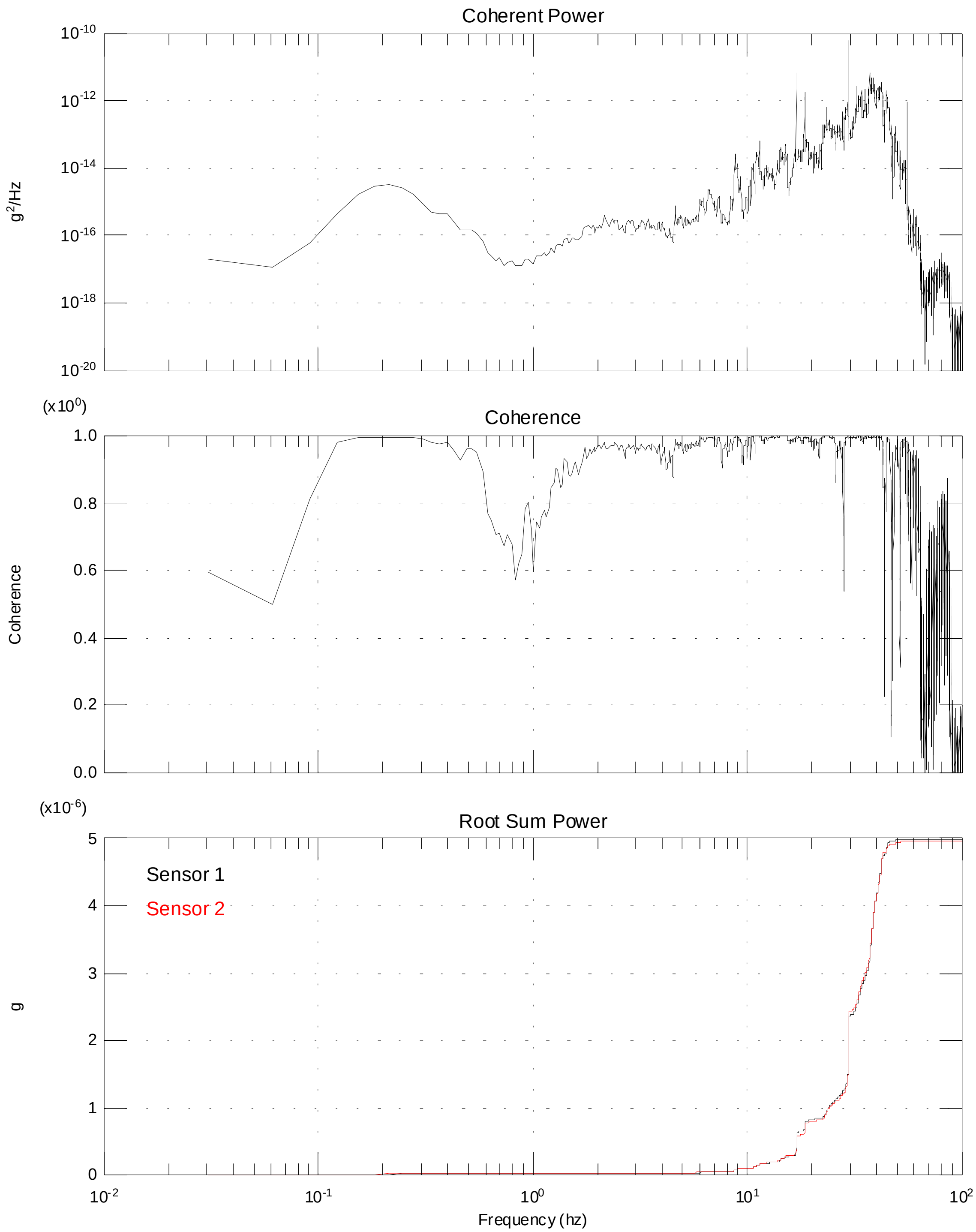

Figure 13. Seismic Disturbances Recorded on the Pad in Room 13 with the Room 9 Air Handler Operating as Measured by Two KS-2000 Vertical Seismometers

2.3.6.2.4 Room 12 Air Handler. The top plot of figure 14 shows the coherent power of one of the KS-2000 vertical sensors, the middle plot shows the coherence between two vertical sensors, and the bottom plot shows the cumulative acceleration recorded from the two sensors. This test also resulted in poor coherence between 1 Hz and 10 Hz, with the exception of the spike a little above 4 Hz. The cumulative acceleration shows that there was not a significant amount of energy recorded at that frequency. The significant energy was at 30 Hz with a magnitude of about 5 micro-*g*. The total cumulative acceleration of the Room 12 air handler is approximately 6 micro-*g*.

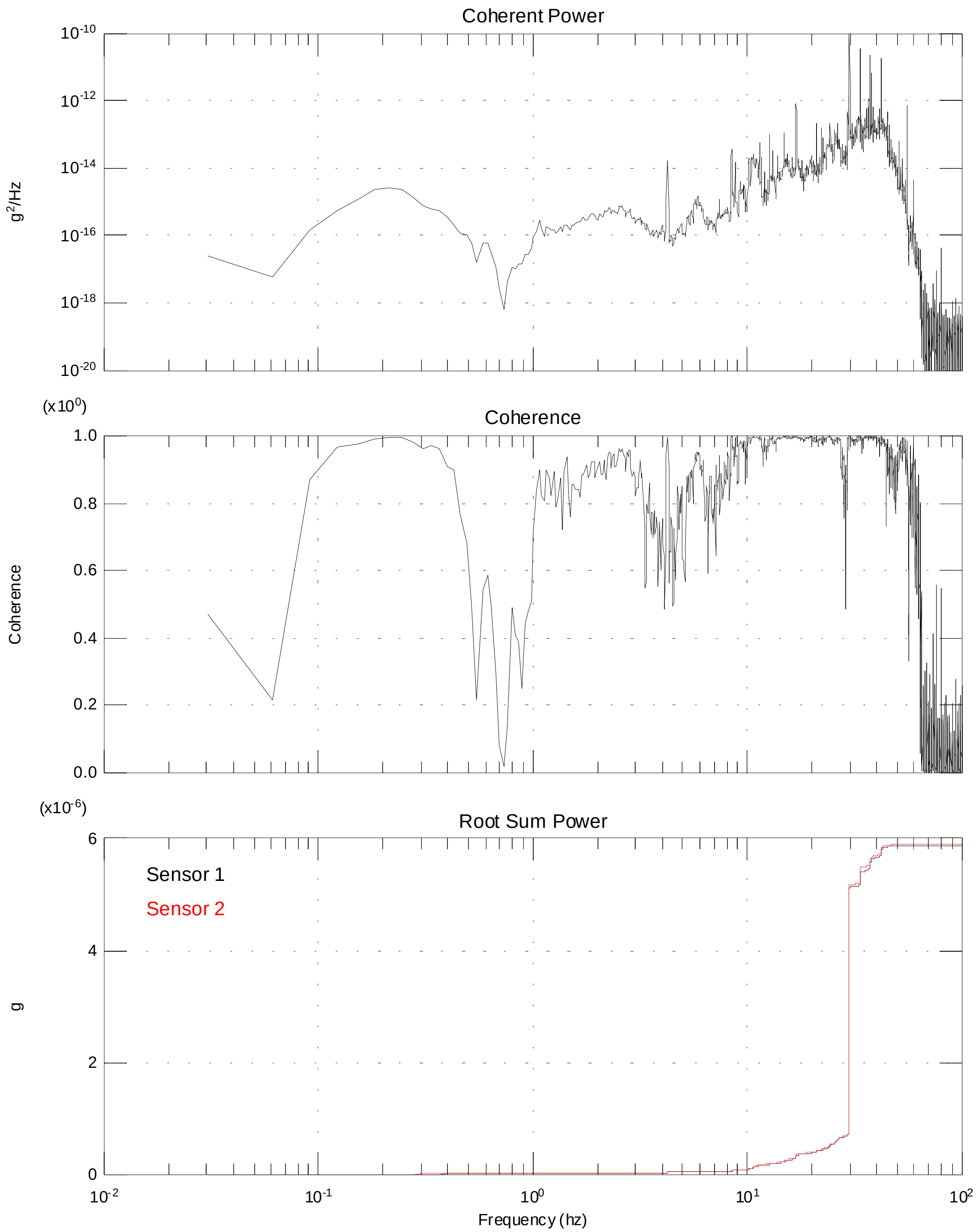

Figure 14. Seismic Disturbances Recorded on the Pad in Room 13 with the Room 12 Air Handler operating as Measured by Two KS-2000 Vertical Seismometers

2.3.6.2.5 Room 13 Air Handler. The top plot in figure 15 shows the coherent power of one of the KS-2000 vertical sensors, the middle plot shows the coherence between two vertical sensors, and the bottom plot shows the cumulative acceleration recorded from the two sensors. The coherence between 1 Hz and 10 Hz was poor. The coherent PSD displays large spikes around 15 Hz and 32 Hz. The cumulative acceleration shows around 2 micro-*g* at about 15 Hz and almost 4 micro-*g* at about 32 Hz. The total cumulative acceleration of Room 13 air handler is approximately 7 micro-*g*.

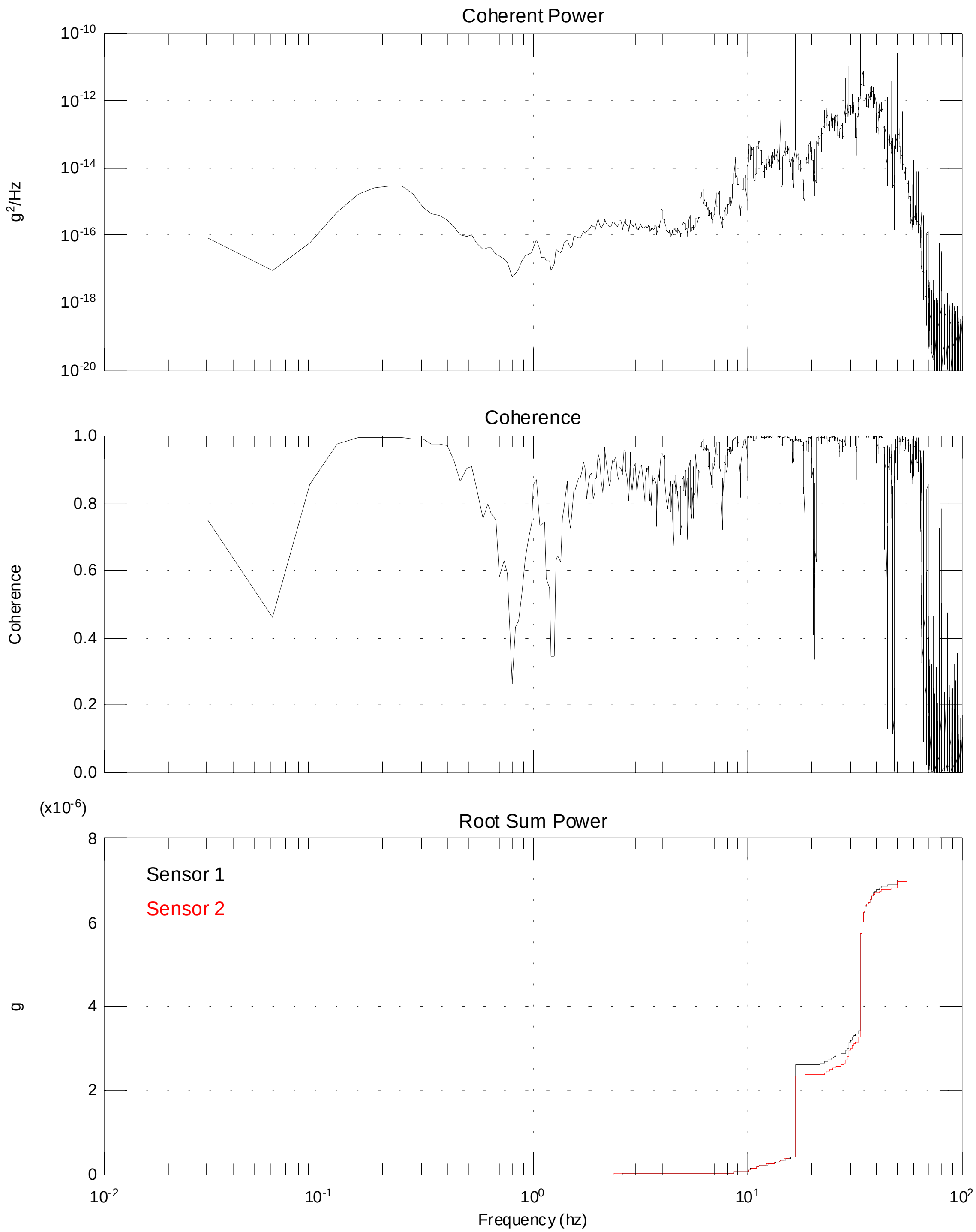

Figure 15. Seismic Disturbances Recorded on the Pad in Room 13 with the Room 13 Air Handler Operating as Measured by Two KS-2000 Vertical Seismometers

2.3.6.2.6 All Air Handlers. The top plot in figure 16 shows the coherent power of one of the KS-2000 vertical sensors, the middle plot shows the coherence between two vertical sensors, and the bottom plot shows the cumulative acceleration recorded from the two sensors. The coherence for this test was well behaved from approximately 1 Hz up to 50 Hz. The coherent PSD shows several spikes co-incident with the spikes that were seen with the individual air handlers. The cumulative acceleration recorded displays several steps that are also co-incident with the steps seen individually. The total cumulative acceleration from this test was almost 12 micro-*g*.

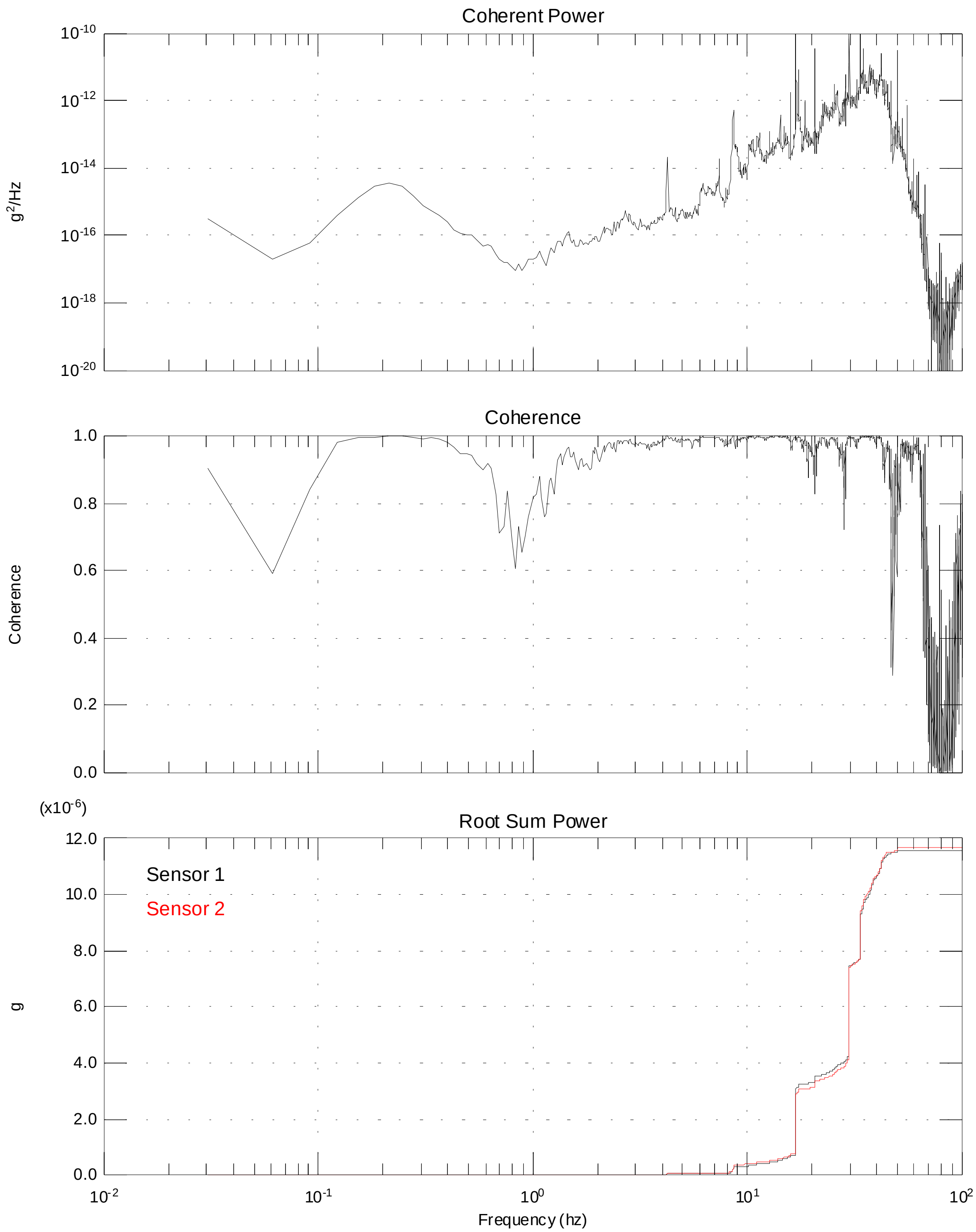

Figure 16. Seismic Disturbances Recorded on the Pad in Room 13 with All Air Handlers Operating as Measured by Two KS-2000 Vertical Seismometers

2.3.6.3 Conclusions. The disturbances caused by all of the air handlers operating simultaneously, 12 micro-*g*, is more harmful to the seismic environment than any other single piece of ESE operating alone. Each of the individual air handlers produced a different amount of total disturbance. The total cumulative acceleration for the administrative air handler is 2 micro-*g*, 5 micro-*g* for the fresh-air air handler, 5 micro-*g* for the Room 9 air handler, 6 micro-*g* for the Room 12 air handler and 7 micro-*g* for the Room 13 air handler. While the air handlers are listed from the least offensive to greatest, any improvement effort undertaken should address all of them collectively since collectively they were the most offensive and efforts undertaken will be similar for each air handler. The values presented will be used as a baseline for future improvements.

During the course of the study, it was observed that some of the mechanical fixtures used to mount the electrical disconnect boxes and fan-belt shrouds were installed such that they bridge across the isolation fixture and the floor of the Mechanical Building. Additionally, the isolators that the air handlers were mounted on are coil springs. It was also noticed that the hot and cold decks that the air was pumped through were mounted vertically on structures bolted directly into the floor (appendix A, figure A-6). These may have been vibrating and creating disturbances. Additionally, the underground concrete tunnels the air passed through to reach the AITL test rooms and to return to the Mechanical Building had 90 degree turns. The buffeting of the air as it flowed through the tunnels could have been a source of some of the disturbances.

2.3.6.4 Recommendation. Improve the isolation of the ESE in order to reduce the seismic disturbances being coupled into the Room 13 test pad (R1).

There does not appear to be a single, simple solution for greatly reducing the disturbances caused by the air handlers. The recommendations below are provided in order of their assumed contribution to reducing seismic disturbance. Check the balance of each of the large squirrel-cage fans and, if needed, rebalance them. Fabricate and install new mounting fixtures to eliminate the bridging, and replace hard electrical conduits with soft, flexible conduits. Replace the coil springs with pneumatic isolators which will provide improved isolation. Undertake future studies to determine the degree to which forced air blowing through air passages degrades the seismic environment. If the buffeting does prove to be a source, turning vanes could be installed to reduce the buffeting.

2.4 Study Objective 4. Determine the vibration generated by all other environmental support equipment and the attenuation being provided by their respective passive isolators.

2.4.1 Room 9 Air Handler.

2.4.1.1 Study Method. One cluster of three PCB™ seismic accelerometers (see appendix C) was placed on the isolation structure supporting the Room 9 air handler with the second cluster placed on the Mechanical Building floor underneath the air handler. One 10-minute test was conducted, which was sufficient to provide adequate seismic data.

2.4.1.2 Results. The top plot in figure 17 shows the PSD from both the air handler and the Mechanical Room floor underneath. The next plot displays the transfer function between the equipment and the floor. The bottom plots show the cumulative accelerations from 1 Hz to 100 Hz for both the air handler and the floor. The transfer function shows between 2 and 3 orders of magnitude reduction across the isolators. The cumulative acceleration plots show that the handler produced 100 milli-*g* across the frequency band and the floor exhibited almost 180 micro-*g*.

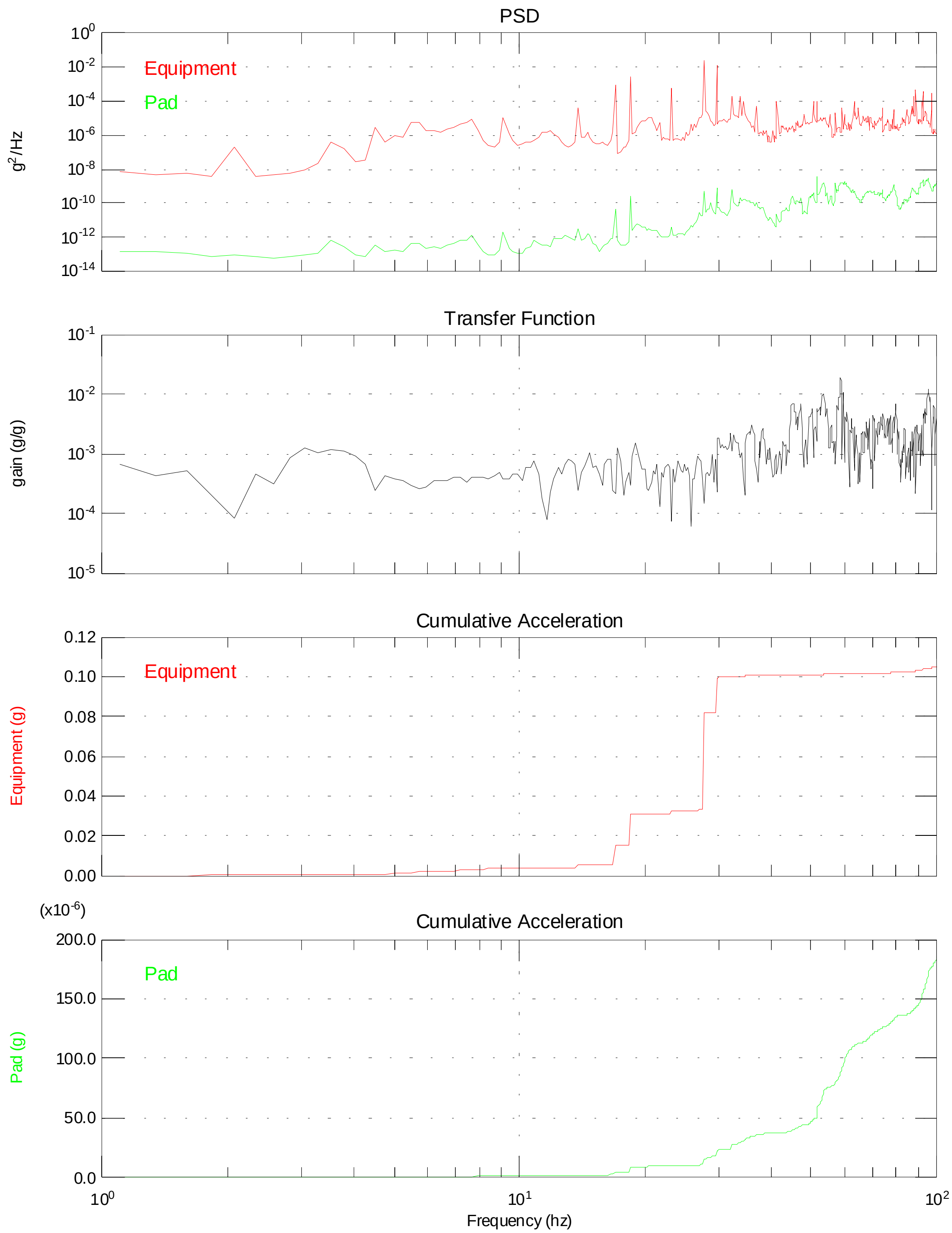

Figure 17. Seismic Disturbances Recorded on the Room 9 Air Handler and on the Concrete Pad as Measured by Two Vertically Oriented PCB™ Seismic Accelerometers

2.4.1.3 Conclusions. The results indicate that the isolation material placed between the air handler and the concrete floor was providing approximately 99.8 milli-*g* of isolation. All the attenuation could not be attributed to isolators. The floor of the Mechanical Building was a large mass of steel reinforced concrete which absorbed a large portion of the energy that was coupled through the isolators. The 99.8 milli-*g* value will be used as baseline for future improvements.

2.4.1.4 Recommendation. Improve the isolation of the ESE in order to reduce the seismic disturbances being coupled into the Room 13 test pad (R1).

2.4.2 Room 12 Air Handler.

2.4.2.1 Study Method. One cluster of three PCB™ seismic accelerometers (see appendix C) was placed on the isolation structure supporting the Room 12 air handler with the second cluster placed on the Mechanical Building floor underneath the air handler. One 10-minute test was conducted, which was sufficient to provide adequate seismic data.

2.4.2.2 Results. The top plot of figure 18 shows the PSD for both the air handler and Mechanical Room floor beneath for this sub-objective. The second plot displays the transfer function. The bottom plots show the cumulative accelerations on the air handler and the floor. The transfer function plot shows between 3 and 4 orders of magnitude reduction across the isolators. The air handler produced 90 milli-*g* across the frequency band while the floor exhibited almost 200 micro-*g* at just below 100 Hz and then increased sharply to a little over 300 micro-*g*.

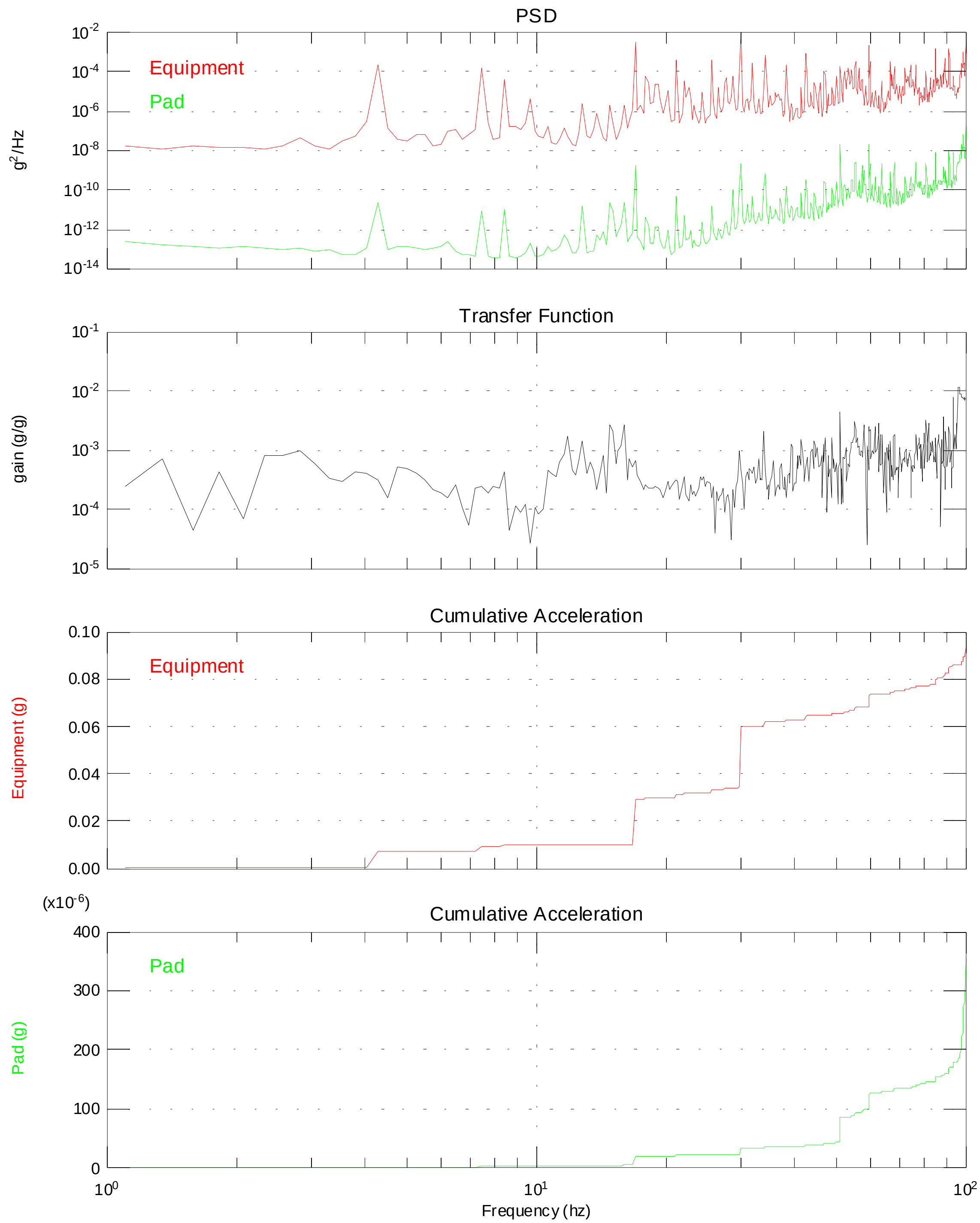

Figure 18. Seismic Disturbances Recorded on the Room 12 Air Handler and on the Concrete Pad as Measured by Two Vertically Oriented PCB™ Seismic Accelerometers

2.4.2.3 Conclusions. The results indicate that the isolation material placed between the air handler and the concrete floor was providing approximately 89.7 milli-*g* of isolation. Again, it is believed that some of the attenuation was due in part to the floor. The 89.7 milli-*g* value will be used as baseline for future improvements.

2.4.2.4 Recommendation. Improve the isolation of the ESE in order to reduce the seismic disturbances being coupled into the Room 13 test pad (R1).

2.4.3 Room 13 Air Handler.

2.4.3.1 Study Method. The Room 13 air handler was fabricated differently than the other air handlers. It was completely surrounded by a sheet metal enclosure (compare appendix A, figure A-4 and appendix A, figure A-5). Consequently, it was not possible to place a sensor cluster on the isolation structure supporting the squirrel cage. In an effort to measure the disturbances being coupled into the floor when this air handler was running, data were collected from the floor near the air handler while it was operating and when it was turned off. A transfer function was determined from the data collected during the two different conditions. Two 10-minute tests were conducted, which was sufficient to provide adequate seismic data.

2.4.3.2 Results. The top plot in figure 19 shows the PSD of the vibrations recorded when the air handler was operating overlaid with the vibrations recorded with the air handler turned off. The second plot shows the transfer function. The bottom two plots show the cumulative acceleration recorded when the air handler was operating and turned off. The cumulative acceleration the air handler off was a little over 12 micro-*g*. With the air handler operating, the acceleration measured a little over 450 micro-*g*. This is a difference of 438 micro-*g.*

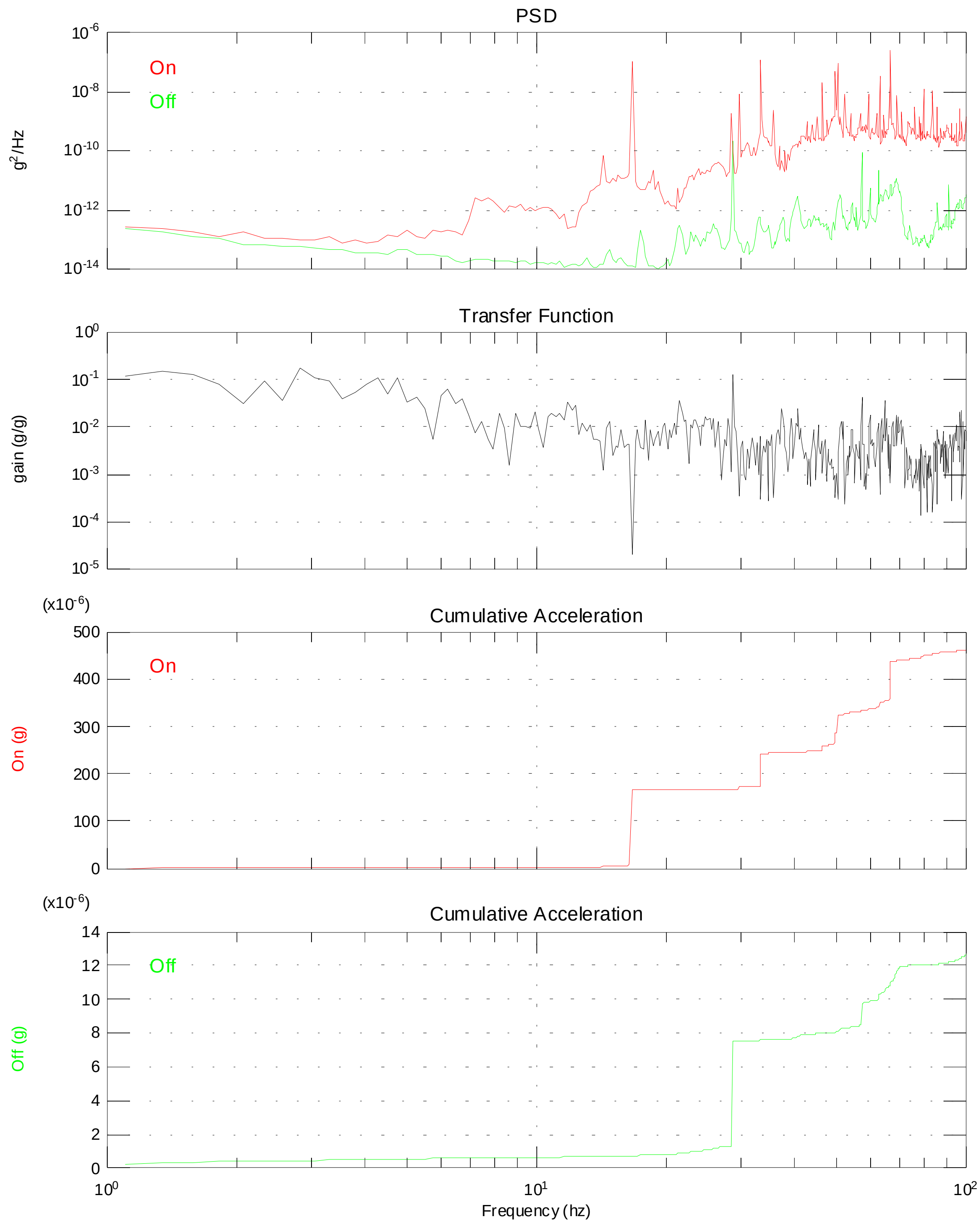

Figure 19. Seismic Disturbances Recorded on the Room 13 Air Handler and on the Concrete Pad as Measured by Two Vertically Oriented PCB™ Seismic Accelerometers

2.4.3.3 Conclusions. These results should not be compared with the results from the other ESE transfer functions because of the difference in test procedures as explained in 2.4.3.1. However, the results demonstrated the increase in seismic activity transmitted into the Mechanical Room floor when the Room 13 air handler was operating. It appears the Room 13 air handler was transmitting more than twice the disturbance into the Mechanical Room floor than any of the other air handlers. Objective 3's Room 13 data showed that the Room 13 air handler contributed more cumulative acceleration than any of the other air handlers, which was consistent with the results of this test.

2.4.3.4 Recommendation. Improve the isolation of the ESE in order to reduce the seismic disturbances being coupled into the Room 13 test pad (R1).

2.4.4 Fresh-air Air Handler.

2.4.4.1 Study Method. One cluster of three PCB™ seismic accelerometers (see appendix C) was placed on the structure supporting the squirrel cage for the fresh-air air handler with the second cluster placed on the Mechanical Building floor underneath the air handler. One 10-minute test was conducted, which was sufficient to provide adequate seismic data.

2.4.4.2 Results. The top plot in figure 20 shows the PSD from both the air handler and Mechanical Room floor underneath the air handler. The second plot shows the transfer function across the isolators. The bottom two plots show the cumulative accelerations of the air handlers and the Mechanical Room floor. The transfer function shows between 2 and 4 orders of magnitude reduction across the isolators. The cumulative acceleration on the air handler was 30 milli-*g* across the frequency band and the floor exhibited a little over 250 micro-*g*.

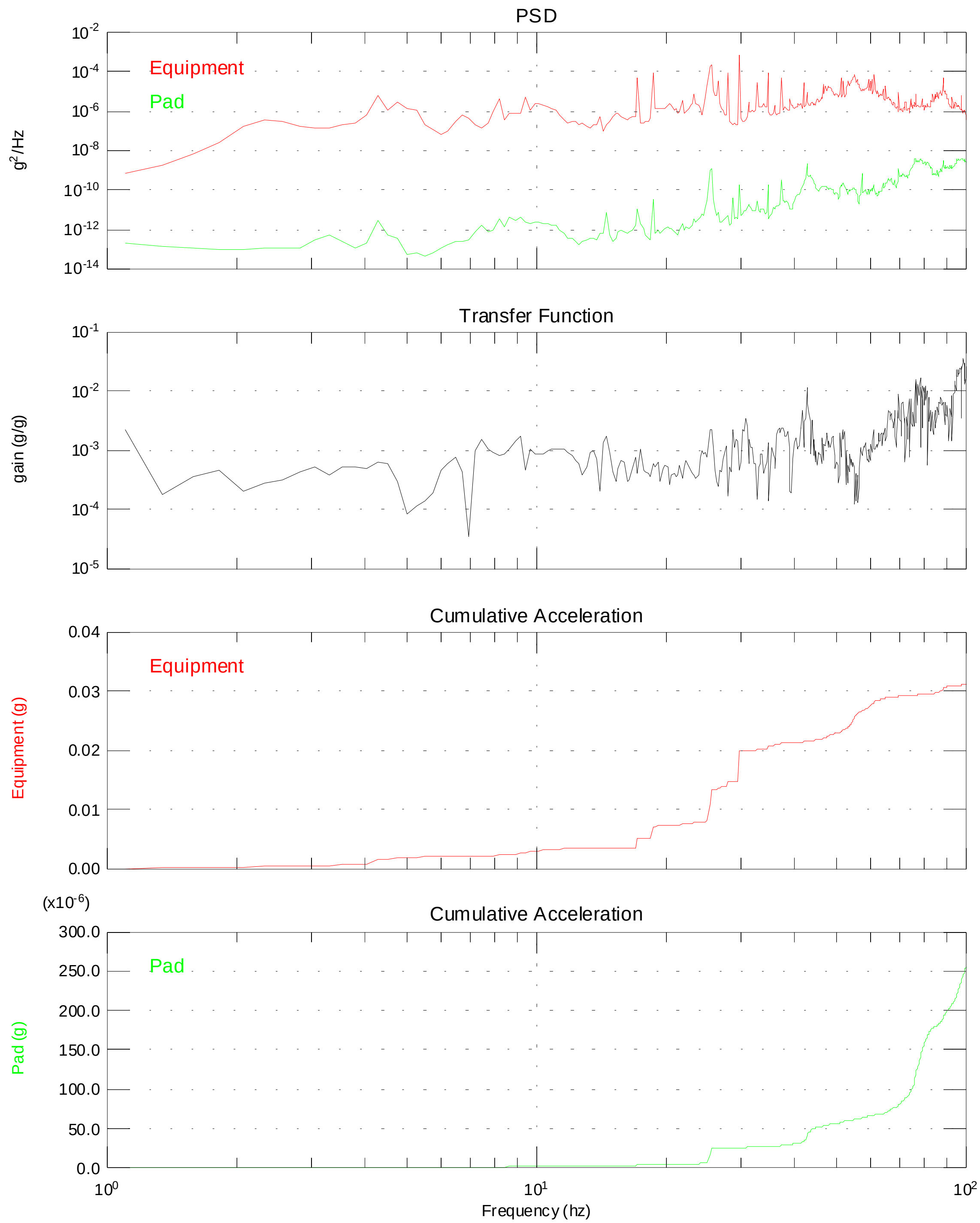

Figure 20. Seismic Disturbances Recorded on the Fresh-air Air Handler and on the Concrete Pad as Measured by Two Vertically Oriented PCB™ Seismic Accelerometers

2.4.4.3 Conclusions. The results indicate that the isolation material placed between the air handler and the concrete floor provided approximately 29.8 milli-*g* of isolation. Although this air handler itself created less cumulative acceleration then the Room 9 or Room 12 air handlers, there was less attenuation at higher frequencies and the Mechanical Building floor experienced similar vibration. However, referring back to objective 3's results, there was no apparent increase in the cumulative acceleration recorded on the pad in Room 13 due to the contribution from this air handler over the Room 9 and Room 12 air handlers. No cause has been developed which adequately explains this behavior. The 29.8 milli-*g* value will be used as baseline for future improvements.

2.4.4.4 Recommendation. Improve the isolation of the ESE in order to reduce the seismic disturbances being coupled into the Room 13 test pad (R1).

2.4.5 Chilled Water Pump.

2.4.5.1 Study Method. One cluster of three PCB™ seismic accelerometers (see appendix C) was placed on the structure supporting the chilled water pump with the second cluster placed on the Mechanical Building floor underneath the air handler. One 10-minute test was conducted, which was sufficient to provide adequate seismic data.

2.4.5.2 Results. The PSD for the chilled water pump and the Mechanical Room floor beside the pump is presented in figure 21. The second plot shows the transfer function across the chilled water pump isolators. The bottom plots represent the cumulative accelerations on the chilled water pump and on the Mechanical Room floor. The transfer function showed a decrease of 1 to 3 orders of magnitude across the isolators. In the frequency band between 10 Hz and 100 Hz, the magnitude of reduction was only 1 order of magnitude. The chilled water pump produced approximately 12 milli-*g* across the frequency band. The floor exhibited 250 micro-*g* across the same band.

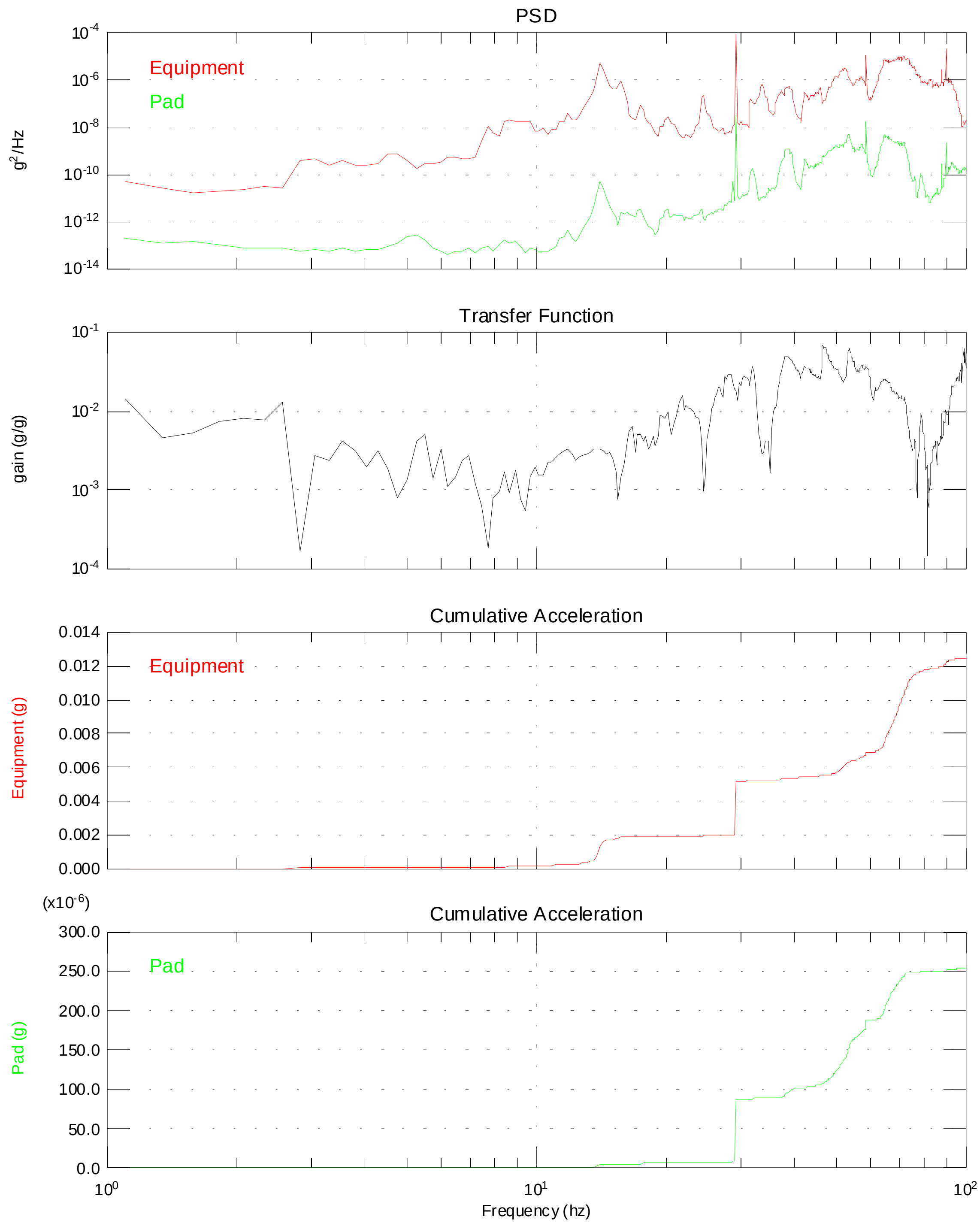

Figure 21. Seismic Disturbances Recorded on the Chilled Water Pump and on the Concrete Pad as Measured by Two Vertically Oriented PCB™ Seismic Accelerometers

2.4.5.3 Conclusions. The results indicated that the isolation material placed between the chilled water pump and the concrete floor provided approximately 11.8 milli-*g* of isolation. The data from this test has shown that the chilled water pump contributed a noticeable amount of seismic disturbance to the floor of the Mechanical Building. The magnitude of the disturbance from this small pump was approximately equivalent to the disturbances seen from the individual air handlers. The 11.8 micro-*g* value will be used as baseline for future improvements.

2.4.5.4 Recommendation. Improve the isolation of the ESE in order to reduce the seismic disturbances being coupled into the Room 13 test pad (R1).

2.4.6 Ultra-Clean Air Supply.

2.4.6.1 Study Method. One cluster of three PCB™ seismic accelerometers (see appendix C) was placed on the ultra-clean air supply (appendix A, figure A-7) with the second cluster placed on the Mechanical Building floor near the structure. One 10-minute test was conducted, which was sufficient to provide adequate seismic data.

2.4.6.2 Results. The top plot in figure 22 shows the PSD for the ultra-clean air supply and the Mechanical Room floor beside the equipment. The center plot, the transfer function, shows the magnitude of the vibrations being coupled into the Mechanical Room floor. The bottom two plots show the cumulative acceleration on the ultra-clean air supply and the Mechanical Room floor respectively. The PSD showed significant spikes at both 50 Hz and 60 Hz. The transfer function showed a decrease between 2 and 3 orders of magnitude with the exception of the higher frequencies. In the higher frequencies, there was 1 order of magnitude attenuation. The cumulative acceleration on the air supply was 27 milli-*g*. The disturbance measured on the mechanical room floor was 400 micro-*g* at a little below 100 Hz and then increased to 500 micro-*g* at 100Hz.

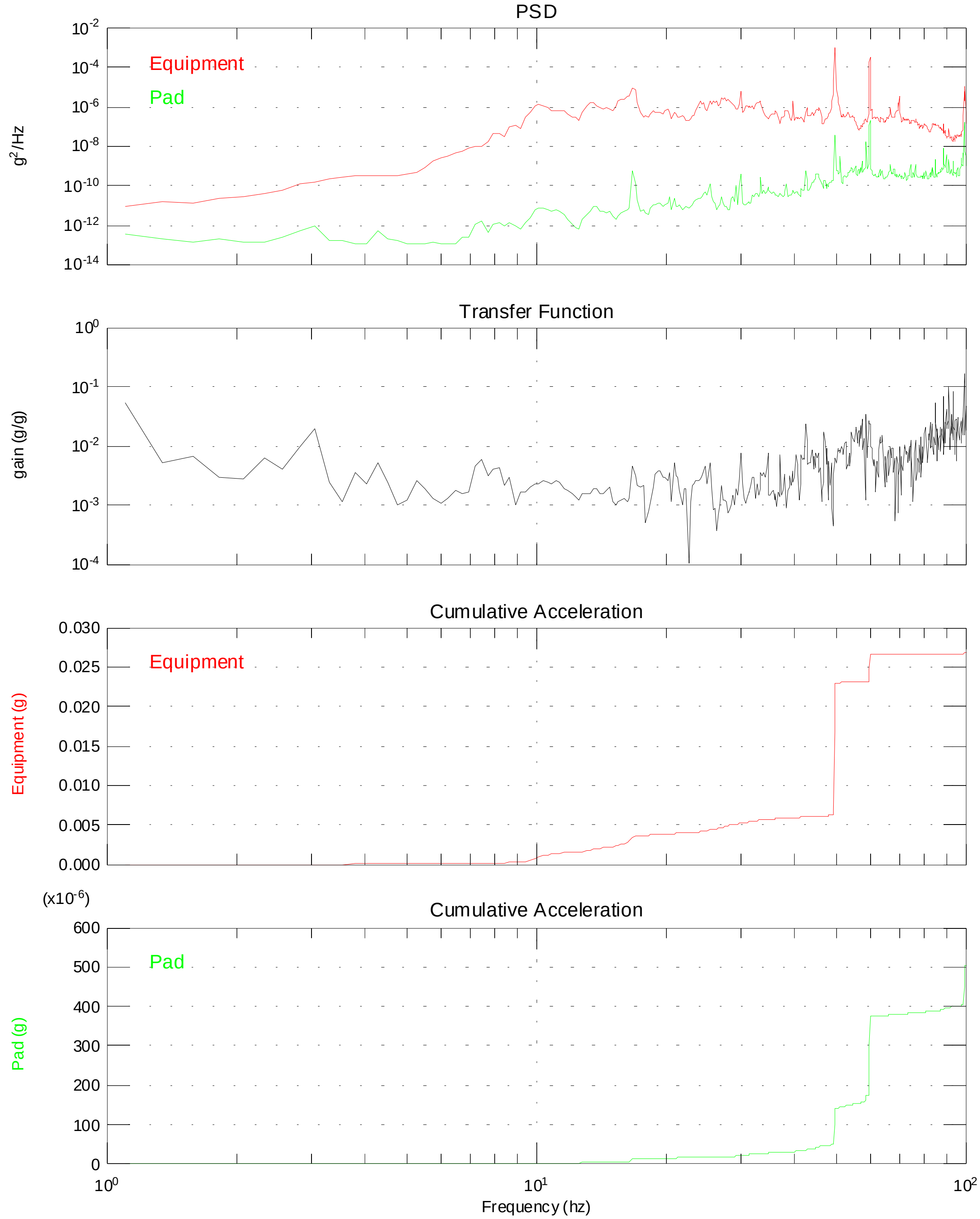

Figure 22. Seismic Disturbances Recorded on the Ultra-clean Air Supply and on the Concrete Pad as Measured by Two Vertically Oriented PCB™ Seismic Accelerometers

2.4.6.3 Conclusions. The results indicated that the isolation material placed between the ultra-clean air supply and the concrete floor provided approximately 26.6 milli-*g* of isolation. Because the ultra-clean air supply was not isolated from the Mechanical Room floor, the attenuation could only be attributed to the Mechanical Room floor. The 26.6 milli-*g* value will be used as baseline for future improvements.

Ultra-clean air is only required when the air bearing rate tables in Rooms 8 and 12 of AITL are being utilized. At all other times, the ultra-clean air supply is left off. It would not be cost effective to improve the isolation on a piece of equipment which is not used on a routine basis.

2.4.6.4 Recommendation. **When ultra-clean air is required, utilize one of the compressors in building 1265 to supply the air to the test beds in AITL (R2).**

2.4.7 Main Commercial Power Transformer.

2.4.7.1 Study Method. One cluster of three PCB™ seismic accelerometers (see appendix C) was placed on the main commercial power transformer (appendix A, figure A-8) with the second cluster placed on the ground near the transformer. Data were collected for 10 minutes, which was sufficient to provide adequate seismic data.

2.4.7.2 Results. The top plot in figure 23 shows the PSD from both the power transformer and the concrete pad the transformer sits on. The center plot shows the transfer function. The bottom plots show the cumulative accelerations on the power transformer and the concrete pad. The PSD presented show that the only significant attenuation lies between 20 Hz and 40 Hz. The magnitudes of the PSD were on the order of 10^{-10} to 10^{-12} g^2/Hz which were well below the magnitudes recorded from the other pieces of ESE. The transfer function showed approximately 1 order of magnitude of attenuation, except between 20 Hz and 40 Hz, where it was almost 2 orders of magnitude. Above 40 Hz, the attenuation decreased to where, at 100 Hz, there was almost no attenuation. The cumulative acceleration on the power transformer was 20 micro-*g* and the pad displayed 6 micro-*g*.

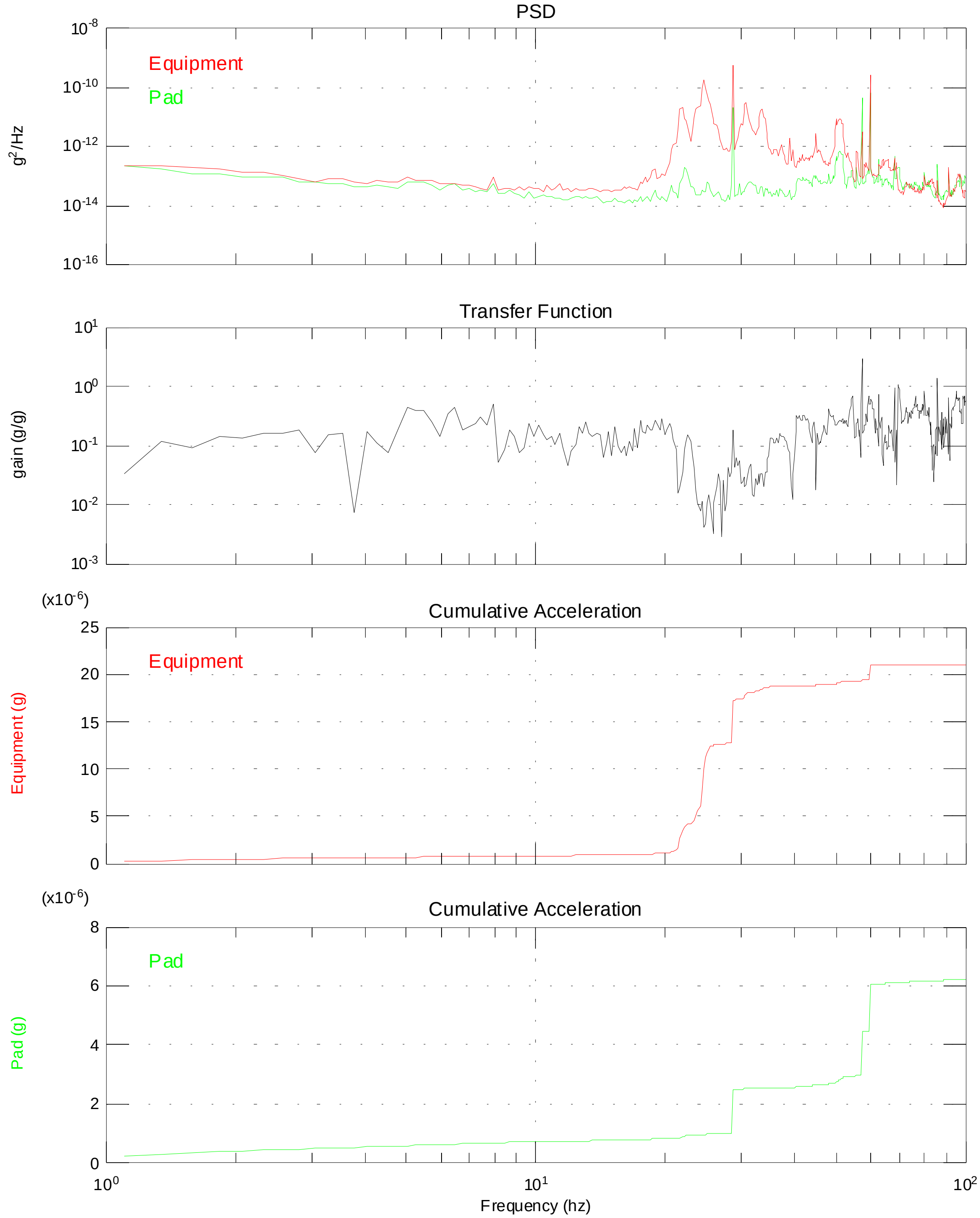

Figure 23. Seismic Disturbances Recorded on the Power Transformer and on the Concrete Pad as Measured by Two Vertically Oriented PCB™ Seismic Accelerometers

2.4.7.3 Conclusions. The data from this test demonstrated that the main commercial power transformer generated a minimal amount of disturbance. The isolation material placed between the transformer and the concrete floor provided approximately 14 micro-*g* of isolation. The 14 micro-*g* value will be used as baseline for future improvements. Improvement in the isolation of the power transformer is not recommended at this time due to the small amount of disturbance it generates.

3 CONCLUSIONS AND RECOMMENDATIONS.

3.1 Conclusions. Overall, the seismic characterization study of AITL was a success and all four of the study objectives were met. The operation of the ESE increased seismic disturbances up to 24 times the ambient level, exceeding requirements for low noise testing. The disturbances produced by the ESE should be reduced by replacing the pneumatic thermostats with a digital unit and improving the isolation materials on selected equipment. Based on total cumulative acceleration, the simultaneous operation of the air handlers produced the greatest seismic disturbance on the test pad in Room 13. Disturbances from individual pieces of ESE are ranked from greatest disturbance to least as follows: the air compressor, the Room 13 air handler, the fresh-air air handler, the Room 9 air handler, the Room 12 air handler, the chilled water pump, the administrative air handler and the chiller.

3.2 Recommendations.

Improve the isolation of the ESE in order to reduce the seismic disturbances being coupled into the Room 13 test pad (R1, pages 13, 16, 19, 22, 35, 38, 40, 42, 44 and 46).

The following improvements are recommended in their order of suggested priority. The established priority is based on the degree of disturbance generated by the ESE tempered with cost and ease of reducing or eliminating its disturbances.

- Replace the current isolation material and place aluminum plates between the top of the isolation material and the chiller base (page 16).
- Replace all thermostats and pneumatic actuators with digital thermostats and actuators, eliminating the need for the air compressor along with its seismic disturbances. Alternatively, make significant improvements to the compressor's isolation (page 19).
- Request that Civil Engineering decommission this unit and activate the second chilled water pump that is presently installed in the Mechanical Building (page 22).
- Check the balance of each of the large squirrel-cage fans and, if needed, rebalance them (page 35)
- Fabricate and install new mounting fixtures to eliminate the bridging, and replace hard electrical conduits, presently transmitting vibration, with soft, flexible conduits (page 35).

- Replace the coil springs with pneumatic isolators which will provide improved isolation (page 35).
- Undertake future studies to determine the degree to which forced air blowing through air passages degrades the seismic environment (page 35).

When ultra-clean air is required, utilize one of the compressors in building 1265 to supply the air to the test beds in AITL (R2, page 48).

THIS PAGE INTENTIONALLY LEFT BLANK.

REFERENCES

The reference listed below may be found by 46th Test Group personnel in the 746th Test Squadron technical library, the program's 6-part folder or at the shared drive address: S:\746TS\Program Management\Programs\AITL STUDY 99930000\TM Documentation. If the program has been archived, digital copies of the documents may be found at L:\746TS\Test Documents\AITL STUDY 99930000. Non-standard test documents which are referenced can be found under tab F (memorandums and miscellaneous documentations) in both the hard copy and digital 6-part folders.

Non-46th Test Group personnel may request copies of the reference by contacting the program manager or the Program Management Flight Chief (comm: 575-679-1767).

1. Advanced Inertial Test Laboratory Baseline Noise Characterization Study; Cleon Barker Consulting; Tularosa NM; January 2006.
2. Central Inertial and GPS Test Facility Study Plan 07-01 (CIGTF-ST-07-01): Seismic Characterization Study of the Advanced Inertial Test Laboratory (AITL); 746 TS, Holloman AFB NM; August 2007.

THIS PAGE INTENTIONALLY LEFT BLANK.

ABBREVIATIONS, ACRONYMS, AND SYMBOLS

A

A/D..........................analog-to-digital

AITL........................Advanced Inertial Test Laboratory

C

CASP+....................Consolidated Analysis Software Package Plus

D

DAS........................data acquisition system

DoD........................Department of Defense

E

ESE........................environmental support equipment

G

g..............................nominal acceleration of gravity on Earth (9.80665 m/s^2)

H

Hz...........................Hertz

L

lb.............................pounds

P

PSD........................power spectral density

V

V.............................Volts

THIS PAGE INTENTIONALLY LEFT BLANK.

APPENDIX A - ENVIRONMENTAL SUPPORT EQUIPMENT

With the exception of the chiller and the main commercial power transformer, the individual pieces of ESE were housed in the Mechanical Building. The Mechanical Building was separated from the AITL facility by approximately 45 feet. Its floor, where most of the ESE were installed, was approximately 8 feet below the ground level around the AITL building. The chiller and main commercial power transformer were installed on concrete pads outside of the Mechanical Building. Also, new measurements of the seismic environment on the test pad in Room 13 were taken. The isolation test pad in Room 13 of AITL was a steel reinforced 15-foot by 22.5-foot by 30-inch concrete pad, located 18 feet below the ground level surrounding the AITL building. Of all the test pads in AITL, this pad provided the most isolation and has been the one used for the past 30 years by the Hubble program. Figures A-1 through A-8 depict photographs of the ESEs which were evaluated during the course of the study.

Figure A-1. Refrigerated Air Conditioner (Chiller)

Figure A-2. Air Compressor

Figure A-3. Chilled Water Pump

Figure A-4. Air Handler

Figure A-5. Room 13 Air Handler

Figure A-6. Hot and Chilled Water Decks

Figure A-7. Ultra-clean Air Supply

Figure A-8. Commercial Power Transformer

THIS PAGE INTENTIONALLY LEFT BLANK.

APPENDIX B - TEST CHRONOLOGY

While this study was conducted from 24 Jul 07 to 26 Mar 08 (See "Test Chronology" on page 2 and table B-1), usable data were only collected starting in late Dec 07. This was due to delays caused by the failure of the A/D converter and computer software issues. Both of these issues were eventually resolved, the first by using a new A/D converter and the second by utilizing a loaner laptop which was compatible with the SnapMaster software. The first attempt to measure the vibrations generated by the air chiller was unsuccessful because the KS-200 and the S-510 seismometers saturated due to the magnitude of the vibrations generated by the chiller. PCB™ seismic accelerometers were selected to replace the KS-2000s and the S-510s. Another problem encountered concerning the chiller was the duration of testing. The chiller could not be kept running for 15 minutes, the normal test duration. When all the other ESE were turned off, there was no demand for chilled water. As a result, the chiller would turn off after only a few minutes. Eventually 4 minutes of data were collected successfully. This was sufficient to characterize the degree of isolation being provided by the passive isolators.

Testing was delayed again in late Feb and early Mar 08 by inconsistencies seen in the readings being collected from the seismometers. After several days troubleshooting this problem, it was determined that the bandwidths of the same model sensor were not identical. Consequently, the outputs did not agree across the entire frequency band. This issue was resolved by pairing up two sensors with similar bandwidths and disregarding the data where the bandwidths were different. The combination of the above issues resulted in the execution of a great number of tests which yielded unusable data.

A limited attempt to calibrate the seismometers in the 746th Test Squadron's Environmental Laboratory yielded promising results. It consisted of generating white random noise of a magnitude of 10 micro-*g* within the bandwidth of 1 Hz to 50 Hz. A calibrated accelerometer, traceable to the National Institute of Standard and Technology, would be employed to provide a reference and record the output of the seismometers. A transfer function would be developed for each of the seismometers output in comparison to the reference accelerometer output. This transfer function could then be used as a scale factor to correct the nonlinearities in seismometers. This effort would be purely labor with no material costs.

During the analysis of the data, it was discovered that the SnapMaster software produced erroneous coherent power results due to the use of unaccepted analysis algorithms. As a result, the data were reprocessed using the Consolidated Analysis Software Package Plus (CASP+).

Table B-1: Test History

Date	Objective	Number of Tests	Location	Equipment Being Exercised
19 Dec 07	4	1	Mechanical Room	All On
	4	1	Mechanical Room	Chilled Water Pump
	4	1	Mechanical Room	Transformer
	4	1	Mechanical Room	Fresh-air Air Handler
	4	1	Mechanical Room	Room 12 Air Handler
	4	1	Mechanical Room	Room 9 Air Handler
	4	2	Mechanical Room	Room 13 Air Handler
10 Jan 08	2	1	Mechanical Room	Air Compressor
	4	1	Mechanical Room	Ultra-clean Air Supply
31 Jan 08	3.1	3	Room 13	All Off
	3.1	1	Room 13	All On
	3.1	2	Room 13	All Off
	3.6	2	Room 13	Room 12 Air Handler
	3.6	1	Room 13	Room 9,12,13 and the Fresh-air Air Handlers
	3.6	1	Room 13	Room 9 Air Handler
	3.6	1	Room 13	Room 13 Air Handler
	3.6	1	Room 13	Fresh-air Air Handler
	3.3	1	Room 13	Air Compressor
12 Feb 08	3.1	1	Room 13	All Off
	3.3	1	Room 13	Air Compressor
	3.5	1	Room 13	Chilled Water Pump
	3.2	1	Room 13	Chiller and Chilled Water Pump

Table B-1: Test History

Date	Objective	Number of Tests	Location	Equipment Being Exercised
14 Feb 08	3.2	2	Room 13	Chiller and Chilled Water Pump
	3.5	1	Room 13	Chilled Water Pump
5 Mar 08	3.1	1	Room 13	All Off
	3.1	1	Room 13	All On
6 Mar 08	3.1	1	Room 13	All Off
9 Mar 08	3.1	1	Room 13	All Off
	3.3	1	Room 13	Air Compressor
	3.5	1	Room 13	Chilled Water Pump
	3.6	1	Room 13	Administrative Air Handler
	3.6	1	Room 13	Room 9 Air Handler
	3.6	1	Room 13	Room 12 Air Handler
	3.6	1	Room 13	Room 13 Air Handler
	3.6	1	Room 13	Fresh-air Air Handler
	3.6	1	Room 13	All Air Handlers
26 Mar 08	3.1	2	Room 13	All On Except Air Compressor
	3.1	1	Room 13	All On
	3.2	1	Room 13	Chiller
	3.2	1	Room 13	Chiller and Chilled Water Pump
	1	1	Mechanical Room	Chiller Under Normal Conditions
	1	1	Mechanical Room	Chiller with All Others Off Except Chilled Water Pump
	1	1	Mechanical Room	Chiller with All Others Off

THIS PAGE INTENTIONALLY LEFT BLANK.

APPENDIX C - TEST EQUIPMENT DESCRIPTION

C-1 Seismometers Description

Three different types of seismometers, each with different sensitivities and bandwidths, were used in this study. One was the model KS-2000 seismometer manufacture by Geotech. It was a single instrument with three single-axis seismometers mounted orthogonally inside the case. It had an advertised sensitivity of approximately 1 nano-*g* and a bandwidth of 0 Hz to approximately 50 Hz. Two of these instruments were used in the study. The study showed that the upper frequency limits were not the same for all the seismometers; some were as low as 40 Hz.

The second model was a Geotech S-510. It is a single axis seismometer with an advertised sensitivity of approximately 1 nano-*g* and a bandwidth of 0.1 Hz to 100 Hz. Six of these sensors were used in the study. As a result of the study effort, it was determined that the upper frequency limits were not the same for all the seismometers, with some as low as 70 Hz. None of the six displayed a linear response below 1 Hz.

The final model was the 393B05 manufacture by PCB Piezotronics. It is a single-axis piezo-seismic accelerometer with an advertised sensitivity of approximately 4 micro-*g* and a bandwidth of 0.7 Hz to 450 Hz. Six of these sensors were also used in the study, when the vibration levels being recorded exceeded the sensitivity range of the KS-2000 and S-510 seismometers.

Two seismometer clusters were created by mounting one KS-2000 and three S-510s onto each of two aluminum plates. Figure C-1 and figure C-2 depict the position of the seismometers on the aluminum plate. Each cluster then provided three axes, one vertical and two horizontal, of seismic monitoring capability. These plates with the sensors were oriented such that one horizontal axis was pointing in the north/south direction and the other horizontal axis was pointed in the east/west direction

.

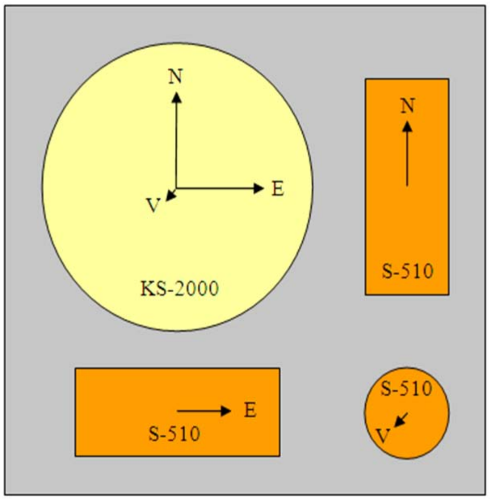

Figure C-1. Seismometer Cluster

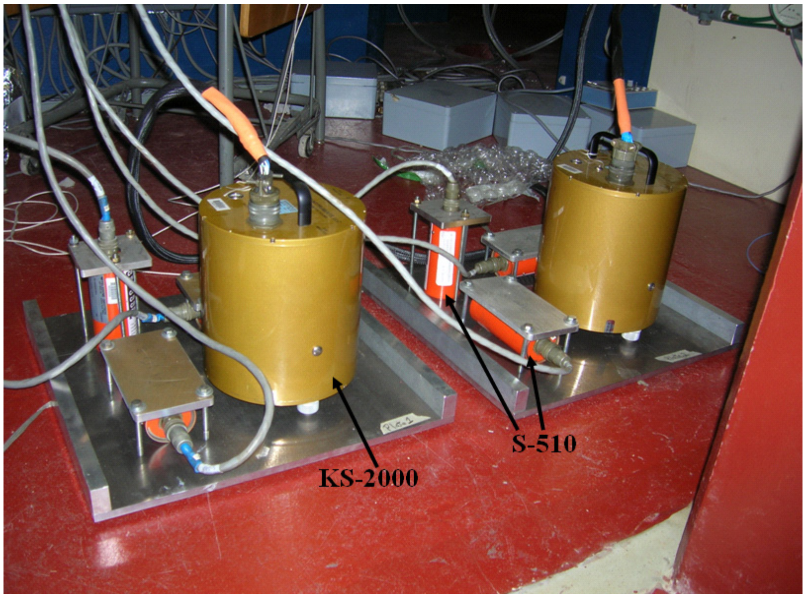

Figure C-2. Two KS-2000 and S-510 Seismometer Clusters

A 3-inch aluminum cube was used to the mount three of the PCB™ seismic accelerometers (see figure C-3). Two of these aluminum cubes were used in this study. When testing, the cubes were oriented such that the two horizontal axes were oriented north/south and east/west, respectively.

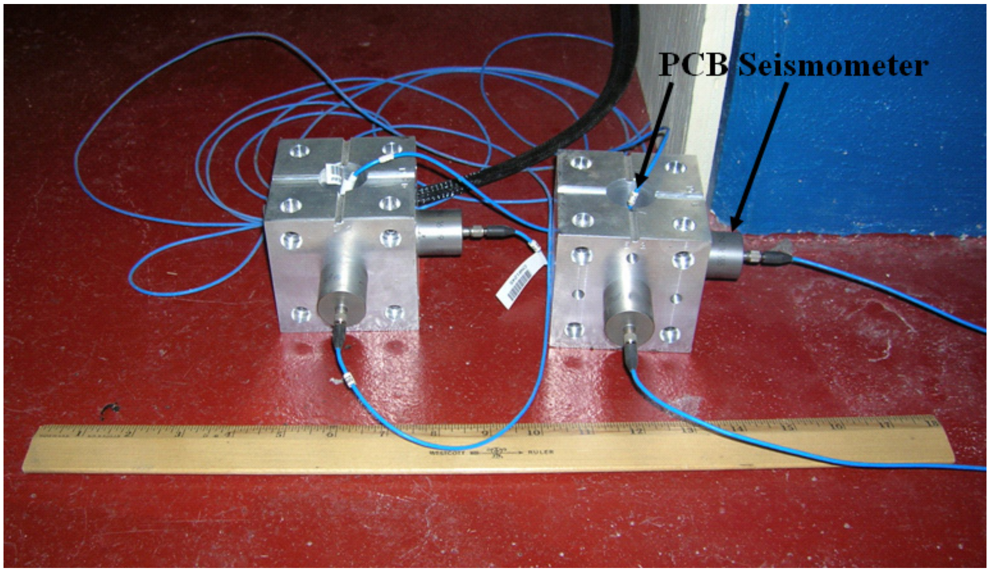

Figure C-3. PCB™ Seismic Accelerometer Clusters

C-2 Anti-Aliasing

The anti-aliasing filter was a model P6000 manufactured by Precision Filters. The filter provided signal conditioning of the seismometer analog signals by filtering unwanted high frequencies as well as providing pre- and post-amplification. Filtering the unwanted high frequencies was necessary to prevent these high frequencies from aliasing back into the recorded digitized data.

C-3 Analog-to-Digital Converter

At the start of testing, a Analogic 16-bit, 16-channel analog-to-digital (A/D) converter with a 20 kHz sampling rate was utilized. This unit failed early in the study and could not be repaired. As a result, a new A/D converter was purchased. The second A/D converter was a DATAQ model DI-720-USB. The D-720 series converter is a 16-bit, 16-channel A/D converter with a 40 kHz sampling rate.

C-4 Computer

The computer used when testing started was a Fieldworks laptop with a Windows 98 operating systems. Because the DATAQ A/D converter required a more robust operating system, a Dell D630 laptop computer with a Windows XP operating system was acquired. Unfortunately, when the data collection software was running, the computer experienced hardware overrun errors. This problem persisted and could not be resolved. In order to continue the study, a loaner laptop was provided by

46TG/XPI. The loaner laptop was a Dell Latitude D610 with a Windows XP Pro operating system. This computer was used for the remainder of the study and did not experience any overruns.

C-5 Software

The software used to collect and analyze that data was an off-the-shelf package published by HEM Data called SnapMaster. The SnapMaster software controlled the A/D converter, the data rates, number of channels sampled and the length of each test. SnapMaster wrote the data to a file on the computer's hard drive in real-time while the data was being collected.

SnapMaster came with built-in routes for performing both time and frequency domain analysis of the collected data. This software was initially used for generating the time domain, power spectral density, coherence, coherent power and root sum power plots until it was discovered that the routines used to generate the coherent power were based on algorithms which are not generally accepted by the analysis community. This resulted in an underestimation of the power by at least an order of magnitude. Once this was discovered, the data were reprocessed using the fully validated Consolidated Analysis Software Package Plus (CASP+) used by 746TS/TGGA.

C-6 Data Acquisition System (DAS)

Figure C-4 shows the data flow through the DAS when the KS-2000s and S-510s were being utilized. When vibration data were collected from individual ESE in the Mechanical Building, the KS-2000s and S-510s were replaced by the PCB™ piezo-seismic accelerometers. The change was made due to the saturation of the KS-2000s and the S-510s.

.

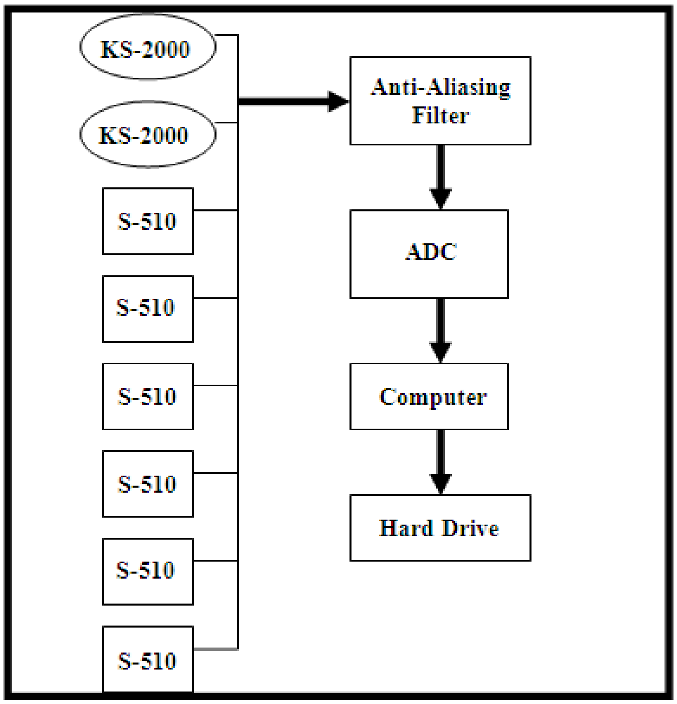

Figure C-4. DAS Data Flow Diagram

THIS PAGE INTENTIONALLY LEFT BLANK.

APPENDIX D - ANALYSIS METHOD

D-1 Time Domain

The data were first plotted in the time domain using the SnapMaster software. The plots were visually inspected to verify that there had been no A/D converter saturation. If the A/D converter received an input voltage exceeding its input limits, it would saturate. Saturation rendered the data useless for frequency domain analysis. The plots were also inspected for undesirable disturbances from unknown sources, such as aircraft flying close the building. These disturbances corrupted the data, making it useless for the purposes of this study.

D-2 Power Spectral Density

The data were next converted into the frequency domain through a fast-Fourier transform and the power spectral density (PSD), called Auto Spectrum by SnapMaster, was plotted with the SnapMaster software. The PSD plots from two parallel sensors were visually inspected to verify that the frequency content of the signals from both sensors were similar.

D-3 Coherence

Because the SnapMaster analysis routine for calculating the coherent power was questionable, it was necessary to convert the data from the recorded SnapMaster format into a Holloman Standard Format. This format allowed the data to be processed using Consolidated Analysis Software Package Plus (CASP+) routines. For future programs, the SnapMaster software should not be used to calculate the coherence.

The coherence between two parallel axes from the same model seismometers was calculated using CASP+. Coherence was an estimate of the identical signal content, in the frequency domain, in the two parallel sensors. All recorded data were made up of true signal and random noise. Random noise, by nature, is incoherent; consequently the coherence plot represented the ratio of true signal and random noise. A ratio of zero represented all random noise and a ratio of one represented all true motion from the sensors.

D-4 Coherent Power

Coherent power was the PSD from one sensor multiplied by the coherence between the two parallel sensors. This plot then represented the true motion sensed by the seismometer in the frequency domain. The output of these seismometers was volts. By applying a scale factor, the volts were converted to units of acceleration or *g*. The units of coherent power were V^2/Hz. After the application of the scale factor, the units were g^2/Hz.

D-5 Root Sum Power

CASP+ provides the ability to calculate the forward root sum power. This is a convenient way of displaying the data for several reasons. First, it converts the data from units g^2/Hz to units of *g*. The units *g* were easier to understand and present the data in a more tangible format. Second, it is a forward summation of the power as frequency was increased. The resulting plot reveals the magnitude of the power across the frequency band. Third, because each individual piece of ESE produces disturbances at different frequencies and magnitudes, the root sum power plot made it easier to identify which piece of equipment produced which disturbance.

D-6 Transfer Function

The transfer function was a plot of the output of a sensor divided by the input from another sensor in the frequency domain. For objectives 1, 2 and 4, the output was the data recorded from a sensor placed on the pad or floor under the ESE. The input was the signal recorded from the sensor placed on the ESE. From this plot, it can be determined how much attenuation was being provided by the passive isolators under the piece of equipment.

DISTRIBUTION LIST

Defense Technical Information Center 1

46th TEST GROUP 2

- CC. 1
- CA. 1

746th TEST SQUADRON 3

- CA. 1
- CAX 1
- Technical Library 1

THIS PAGE INTENTIONALLY LEFT BLANK.

THIS PAGE INTENTIONALLY LEFT BLANK.